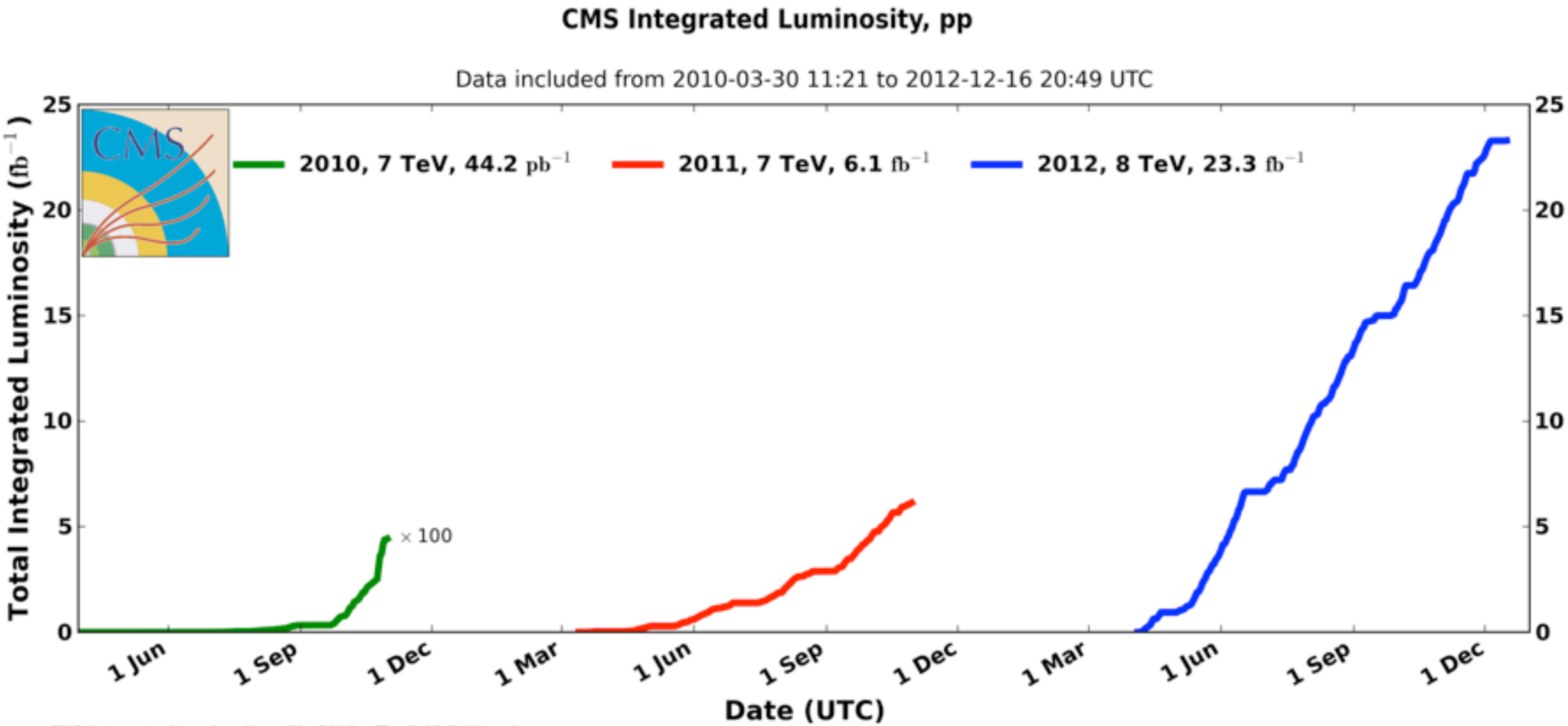
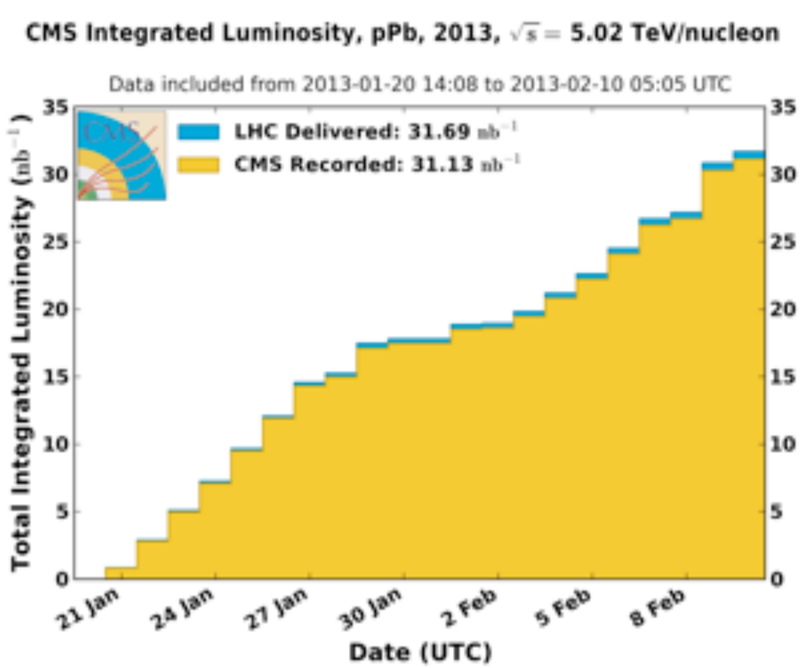
Recent results from CMS

Yurii Maravin (KSU)
on behalf of the CMS collaboration

Wine and Cheese Seminar, 03/15/13

Thanks LHC for fantastic 3 years!



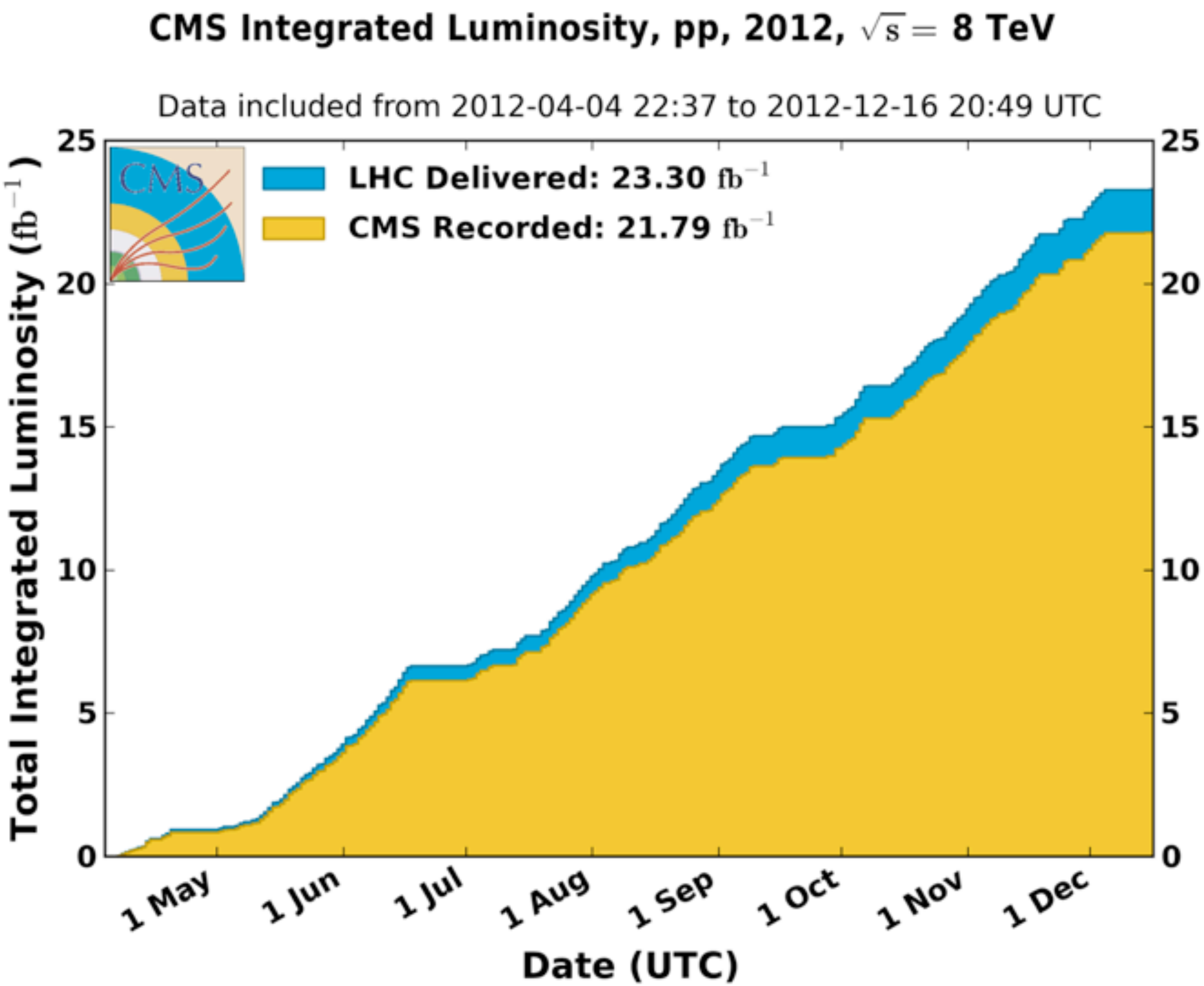


Comments (21-Feb-2013 09:05:25)
Phone:77600

*** END OF RUN 1 ***
No beam for a while. Access required
time estimate: ~2 years

Performance is impressive

- CMS detector operates at ~94% efficiency
  - Most of the results to be shown today use the full data set



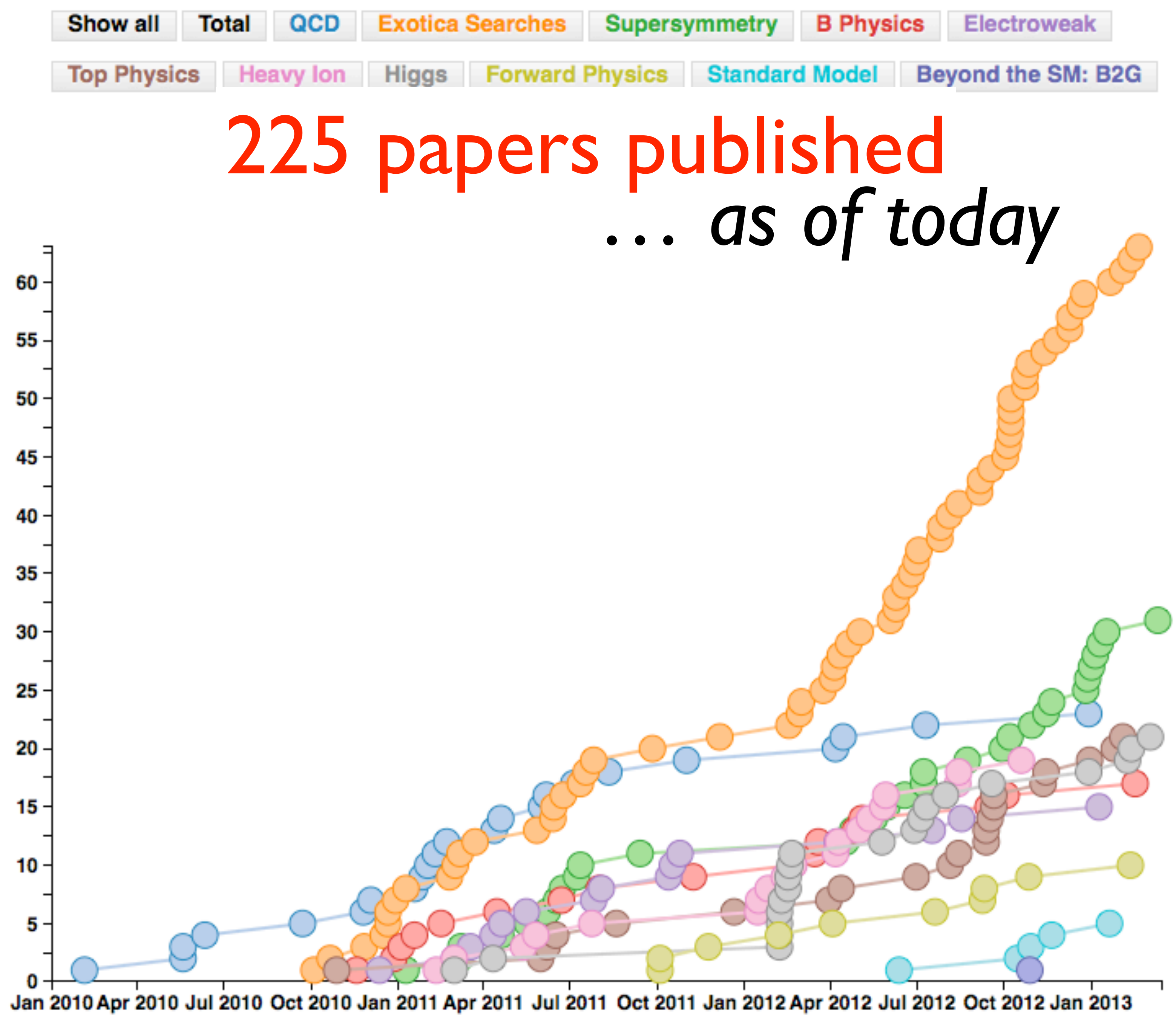
A very prolific 3 years

- Public physics results info:

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

225 papers published

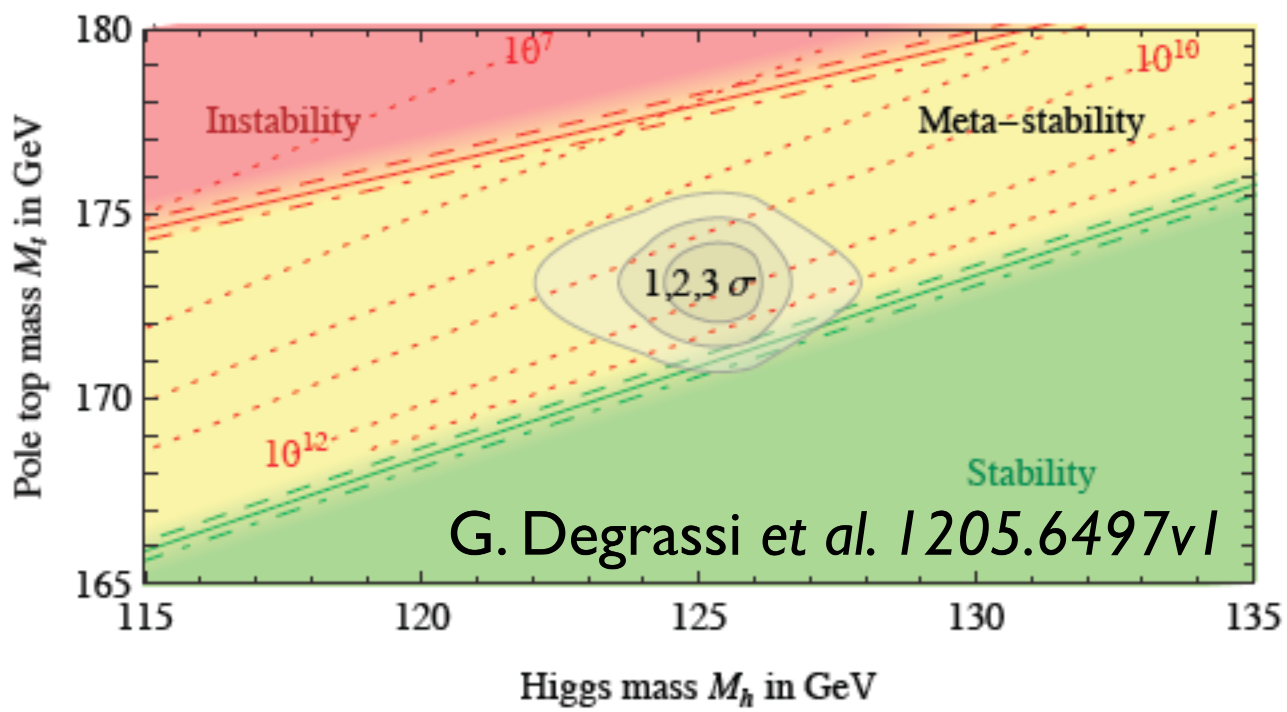
… *as of today*

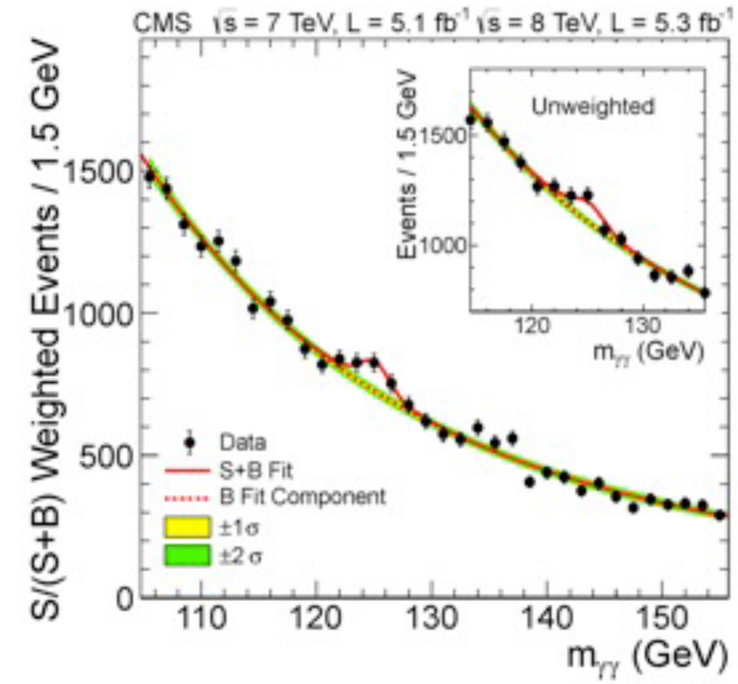


http://cmsdoc.cern.ch/~mccauley/cmsphysics/

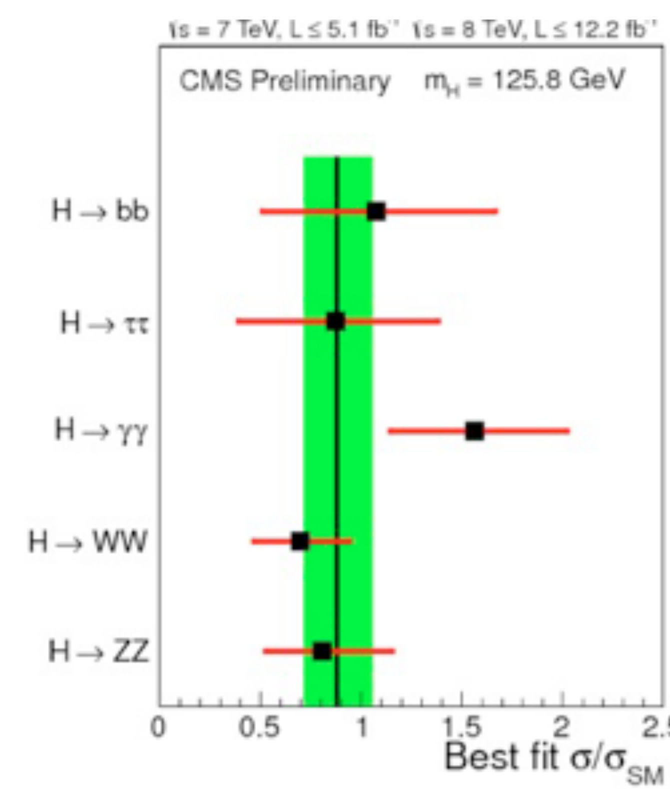
New addition

- The most exciting results from the LHC is a discovery of a new SM Higgs-like boson in 2012
  - Mass is 125.8 ± 0.6 GeV
    - A very interesting mass range: stability of the Higgs potential is excluded at ~2σ





  - Signal strength seems to agree with the SM predictions…



- What are news from CMS in 2013?

Outline of the talk

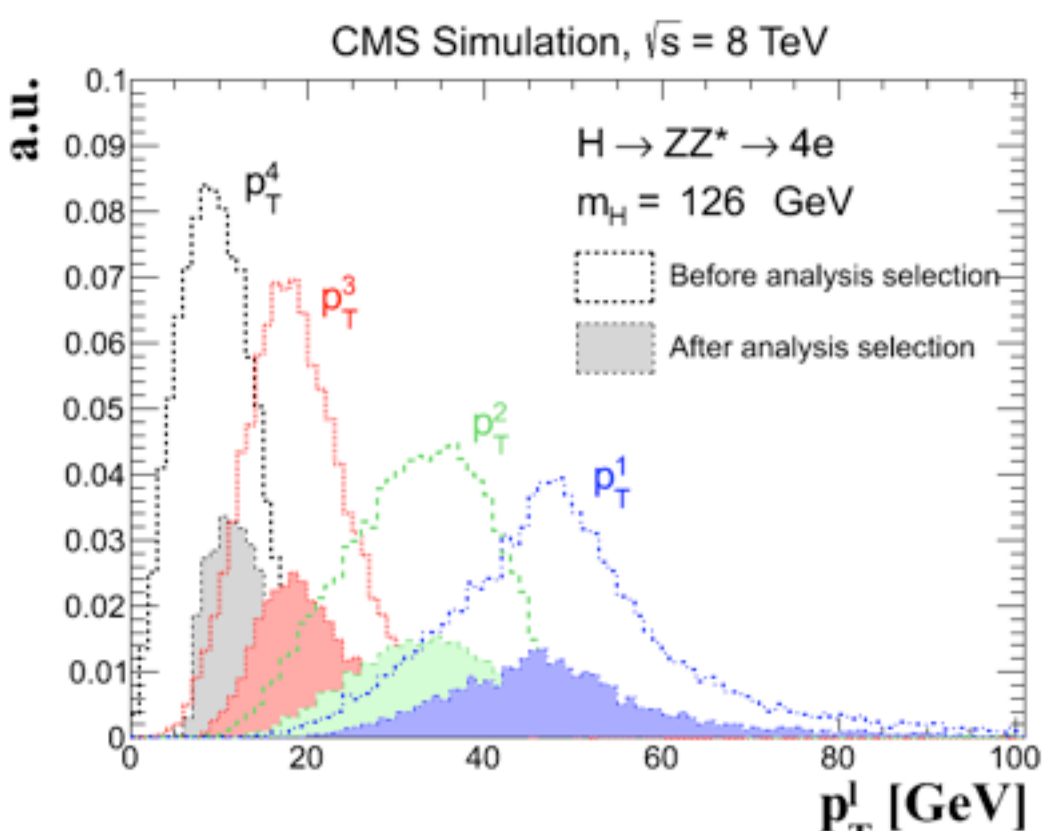
- Recent Higgs results from CMS with full data set
  - $H \to ZZ \to 4\ell$
  - $H \to WW \to 2\ell 2\nu$
  - $H \to \tau\tau$

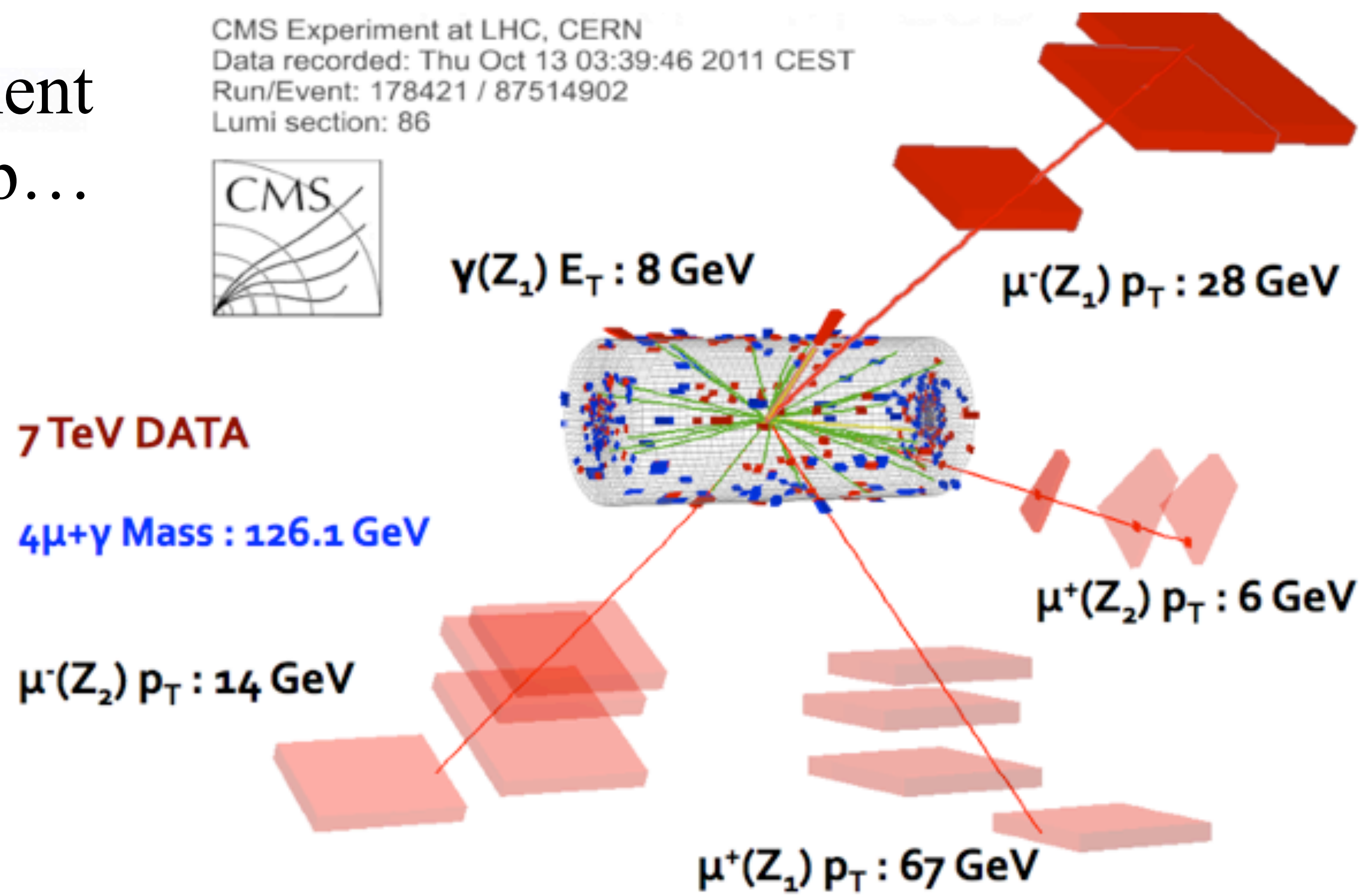
  } spin-parity studies
- New results from searches for SM extensions
  - Search for natural SUSY in multi(b)jets and MET
  - Search for heavy resonances in dilepton and lepton + MET signatures
  - Searching for lots of invisible things with monojets

Study of H→ZZ production

HIG-13-002

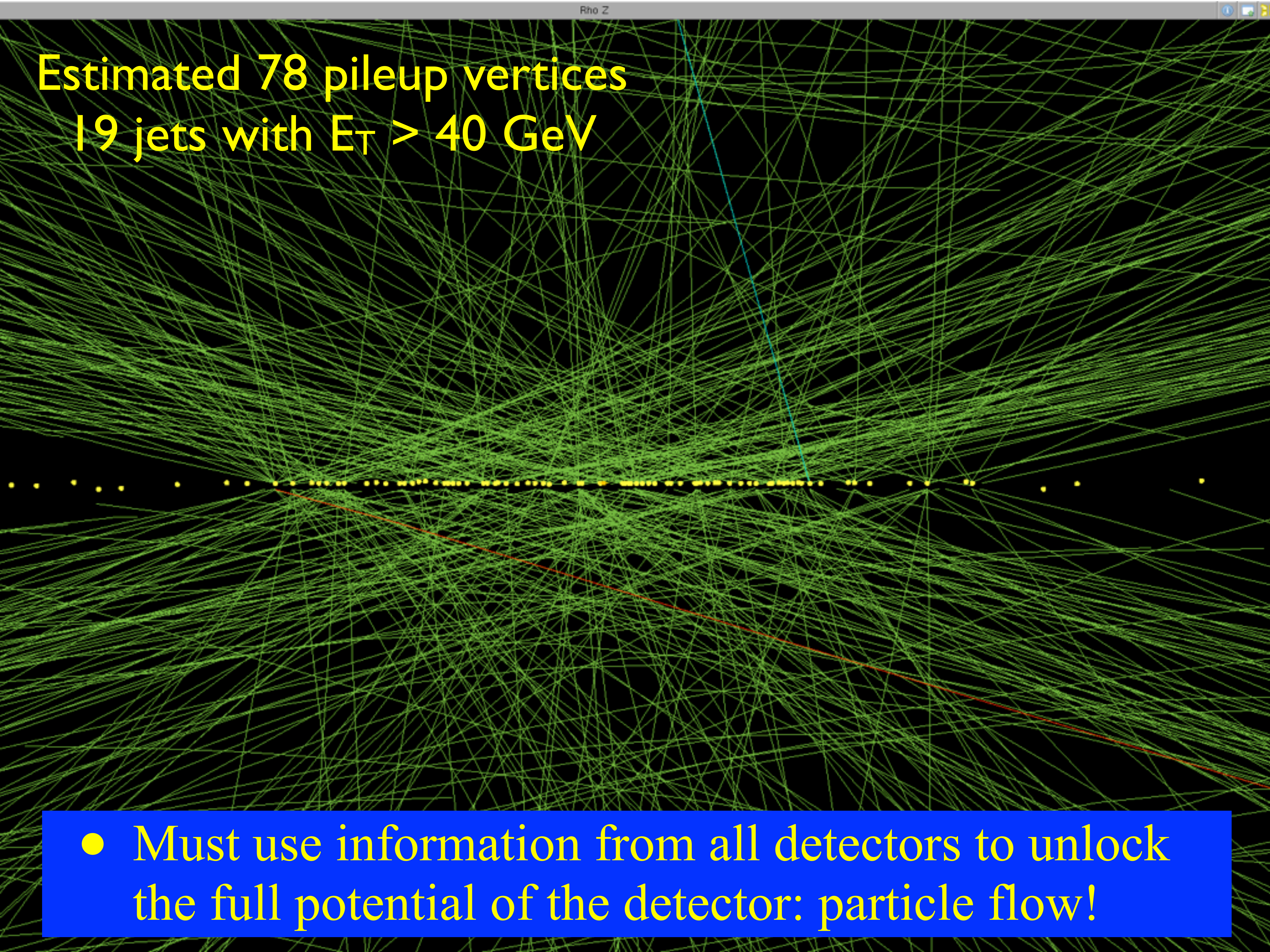
- Four isolated leptons from the same vertex
  - Good mass resolution, and *excellent S/B ratio*
  - Backgrounds: ZZ continuum, Z+jets, $Zb\bar{b}$, $t\bar{t}$
- Very demanding analysis due to soft isolated leptons in the final state
  - Identification, measurement of p_T, dealing with pileup…



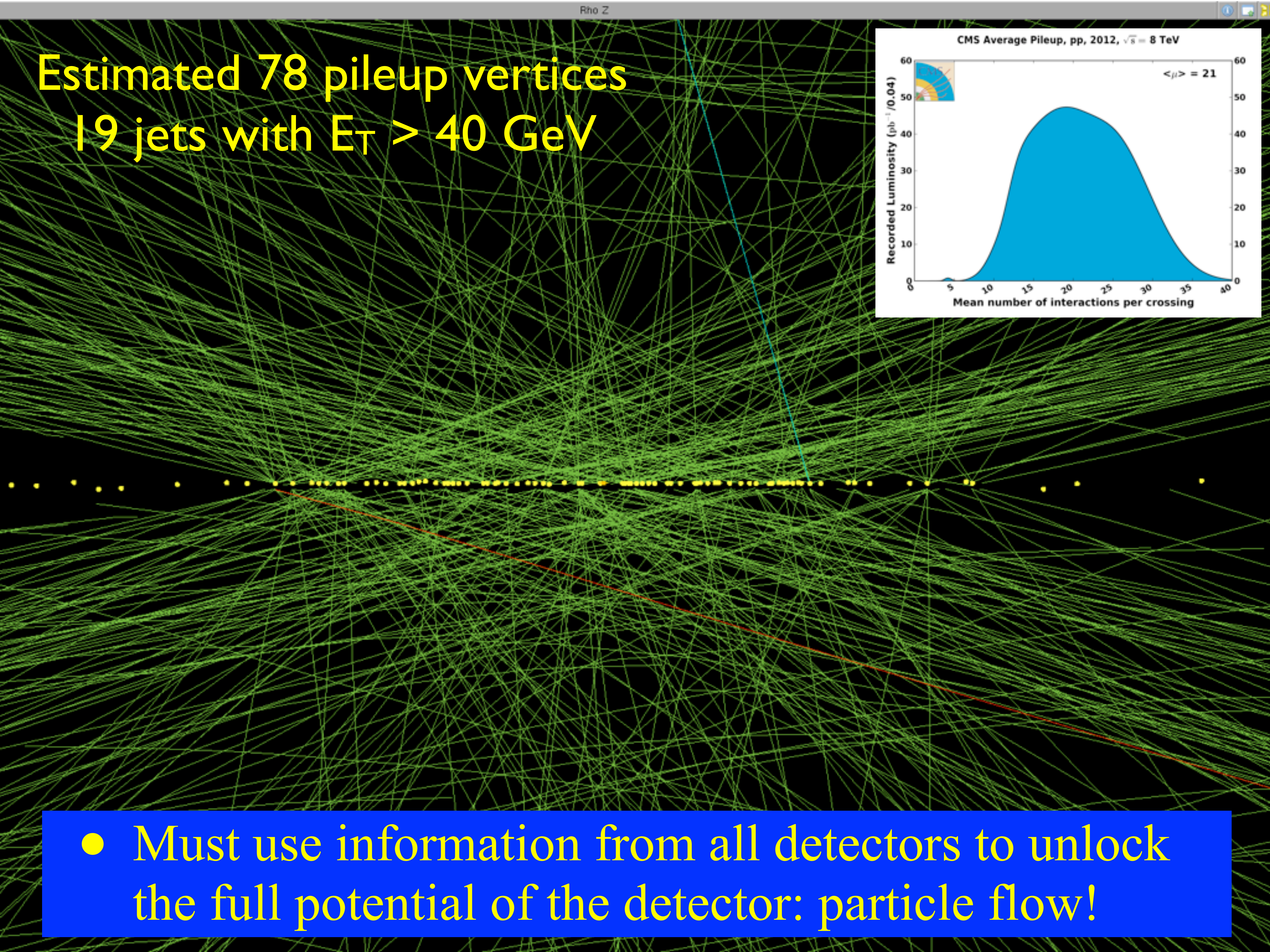


Estimated 78 pileup vertices

19 jets with E_T > 40 GeV



- Must use information from all detectors to unlock the full potential of the detector: particle flow!



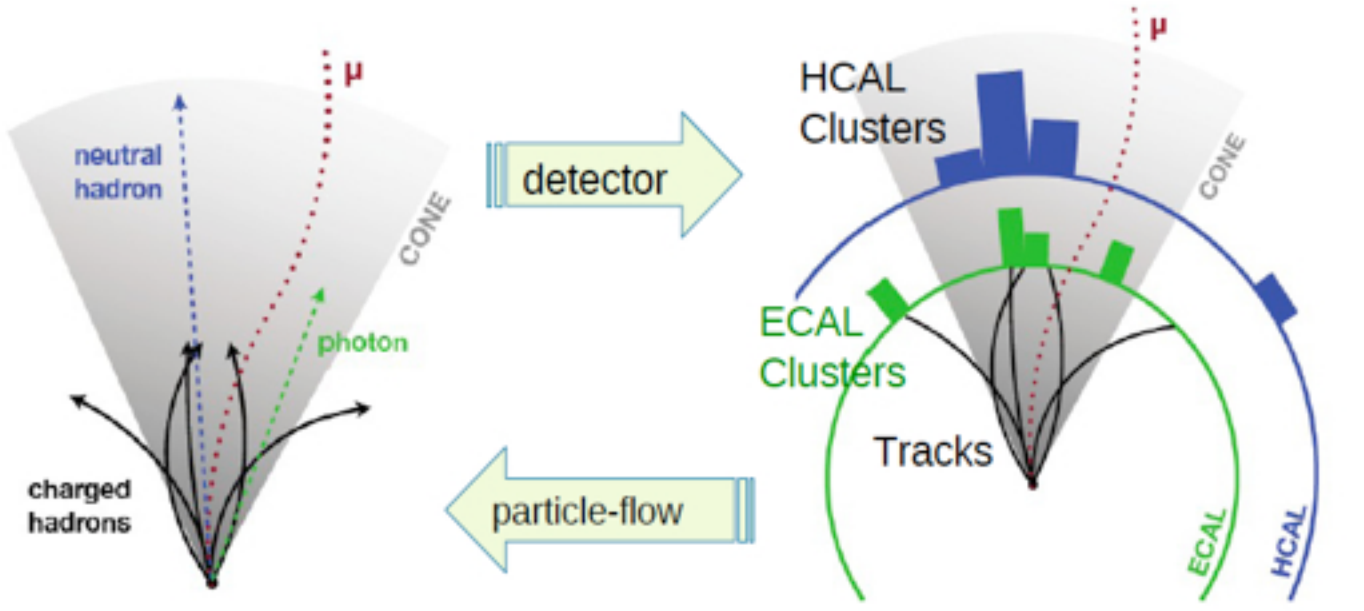
Estimated 78 pileup vertices

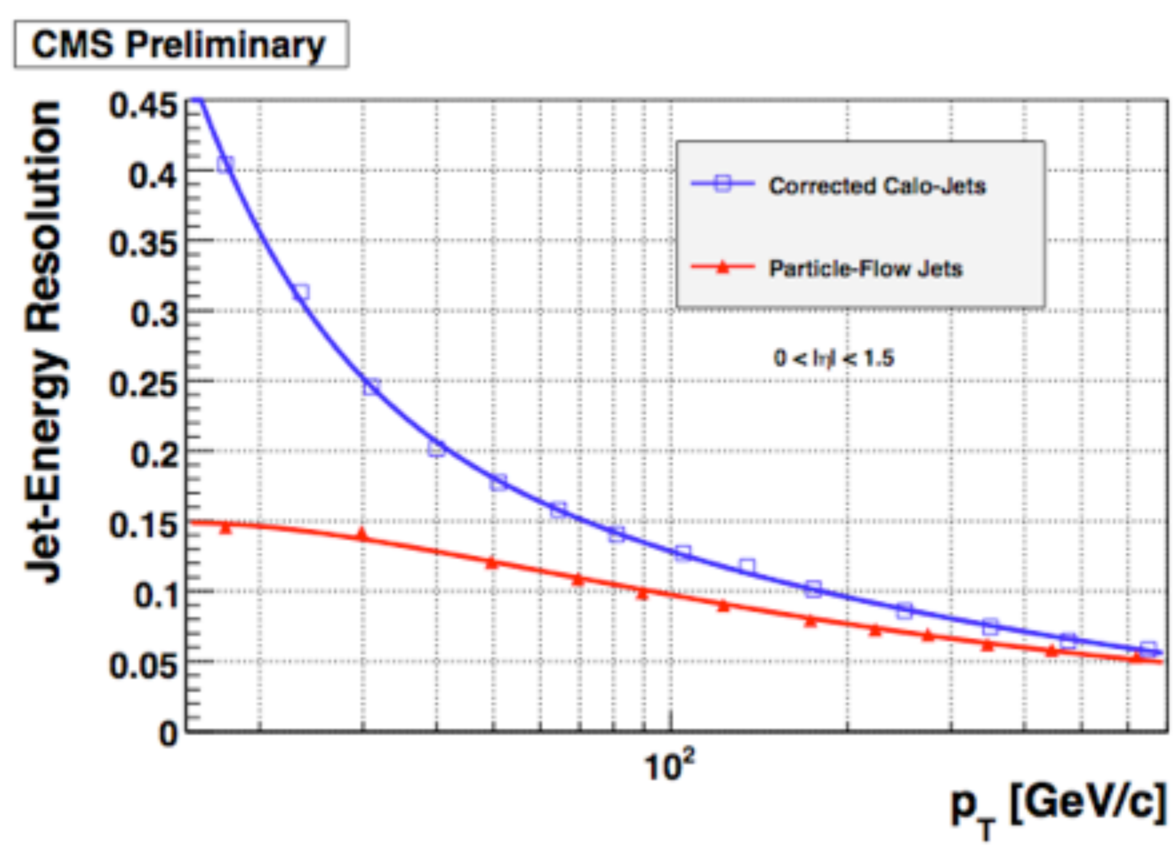
19 jets with $E_T > 40$ GeV

- Must use information from all detectors to unlock the full potential of the detector: particle flow!

Particle flow

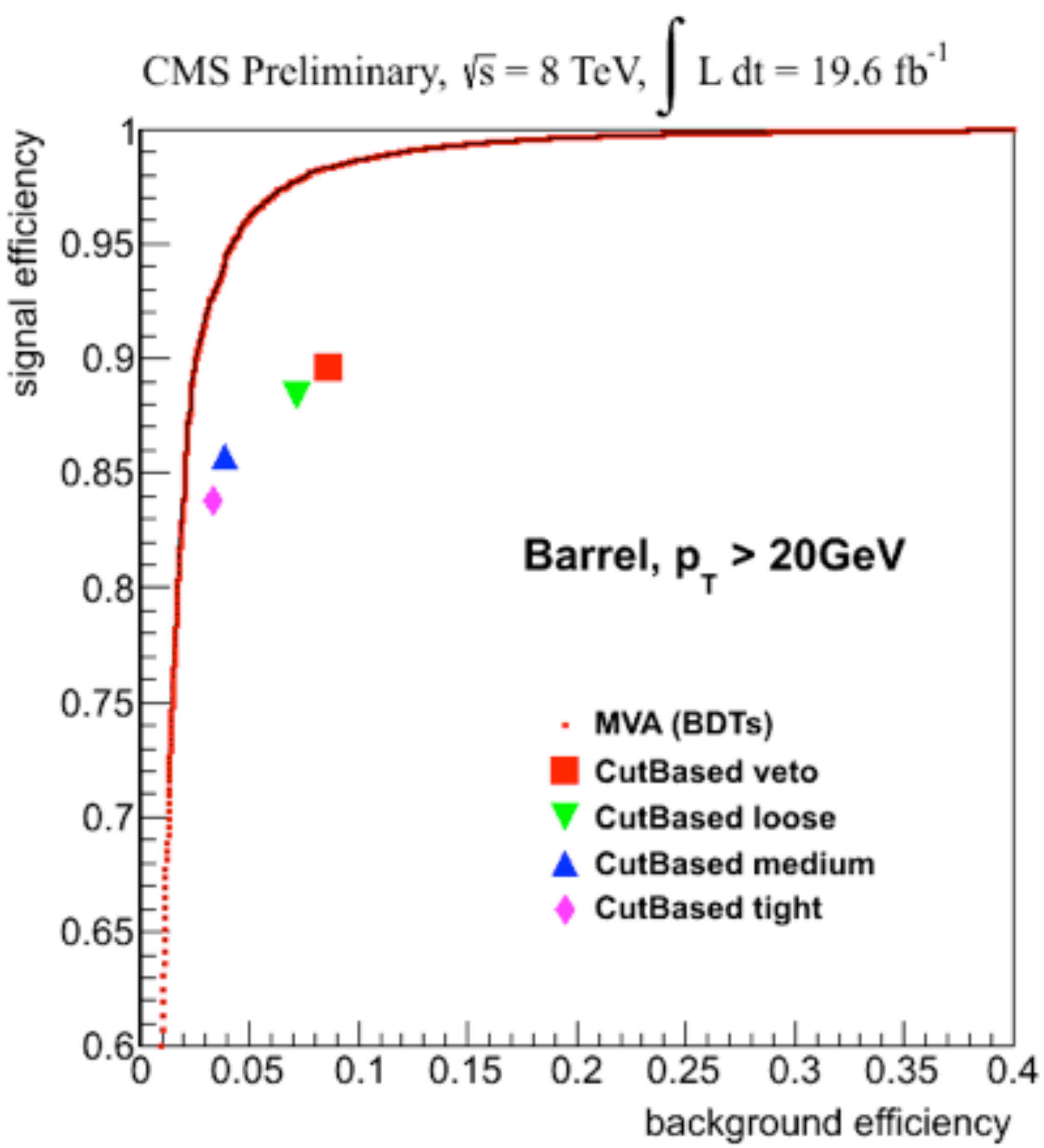
- Excellent tracker + 3.8T magnetic field + fine-segmented ECAL
- Use information from all the sub-detectors to reconstruct individual particles in the event
  - Form electron, muon, photon, charged and neutral hadron candidate lists
  - Improves energy and resolution as well as spatial resolution of energy flow in jets

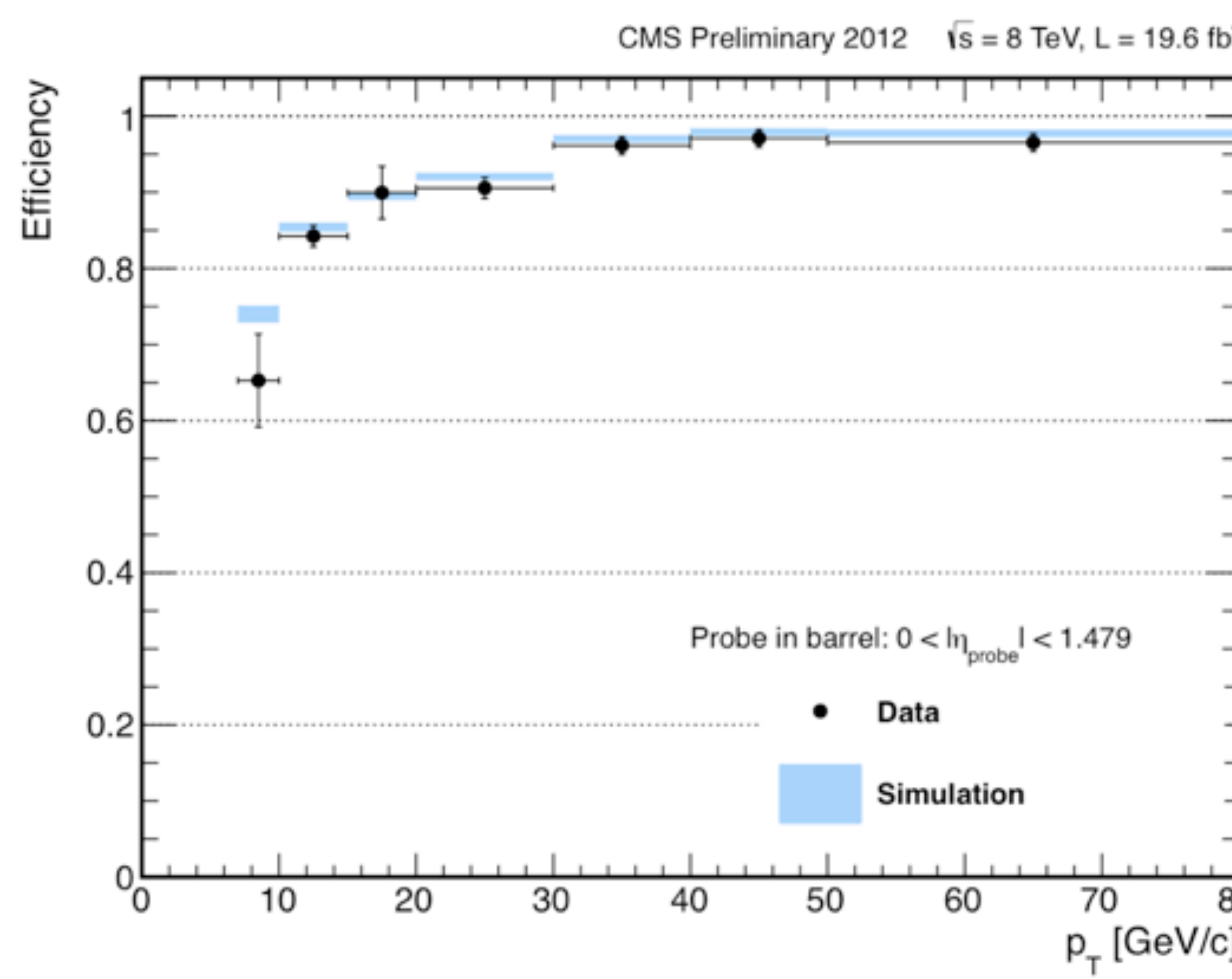




Lepton identification

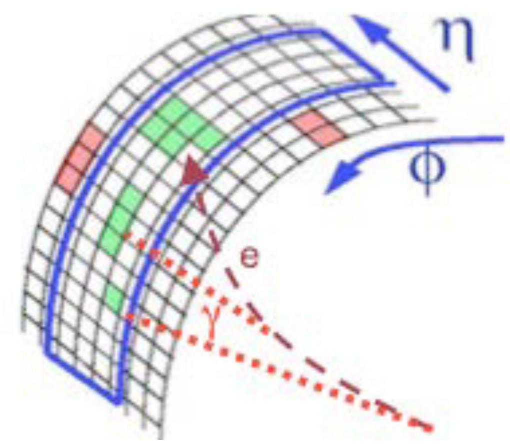
- Using particle flow significantly boosted the performance of the identification/isolation criteria
  - Using MVA techniques made further improvements, including the pileup mitigation

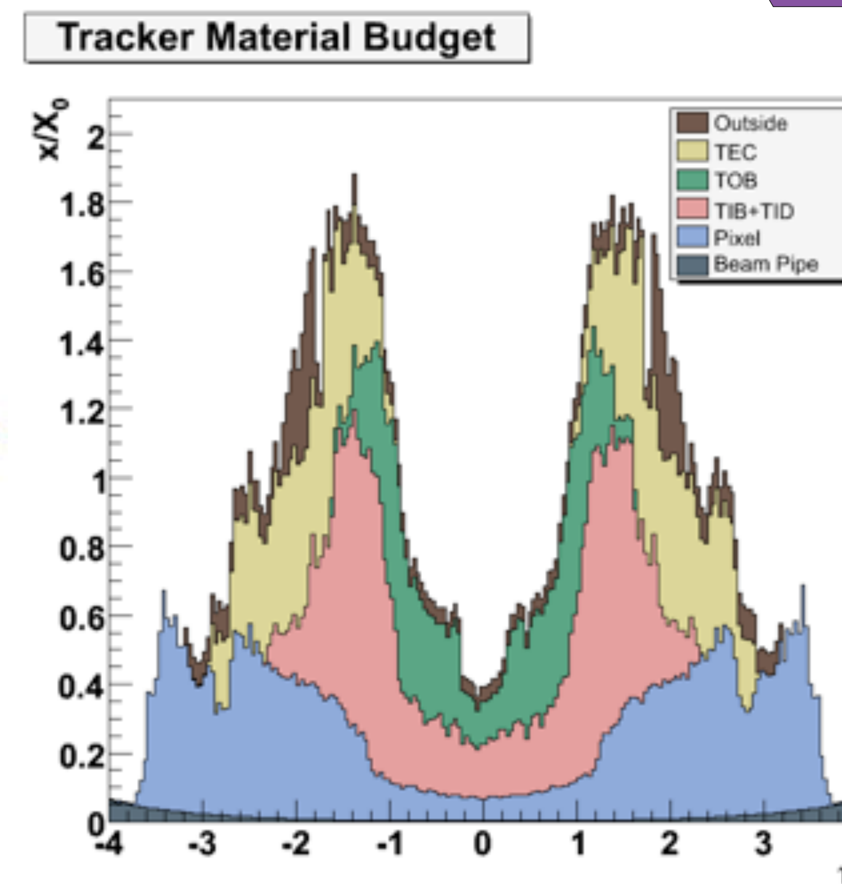




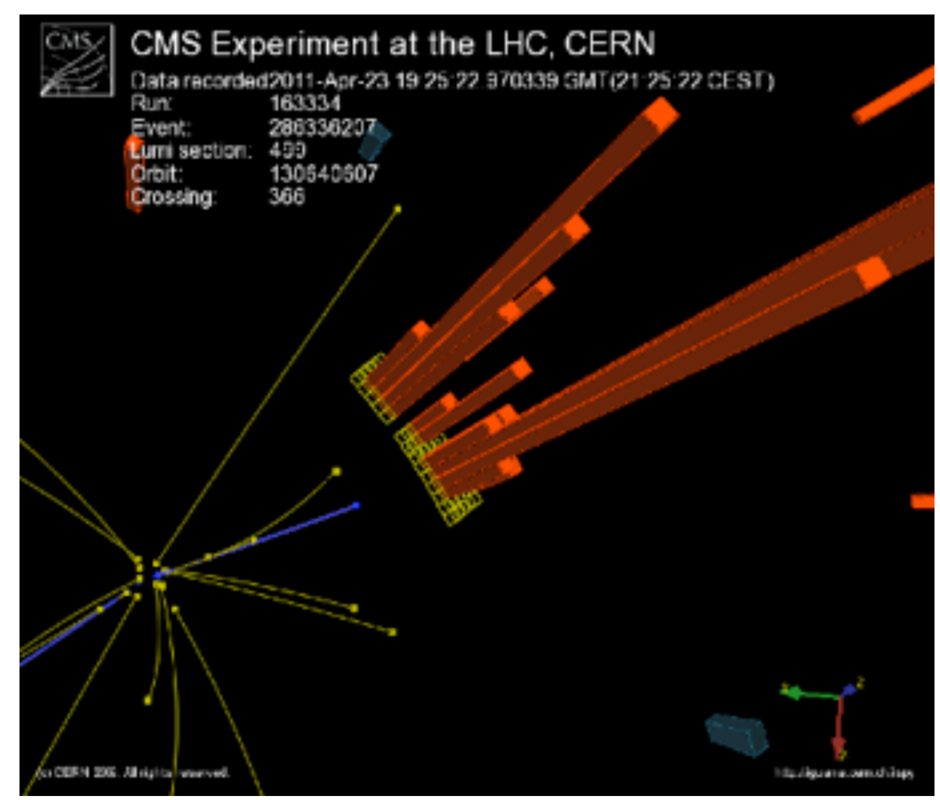
EM Energy scale & resolution

- Several sources of energy loss for electrons and photons:
  - Large amount of material in front of the ECAL results in strong Bremsstrahlung
    - Loss of energy is most pronounced in soft electrons
  - Crystals lose transparency with radiation
    - Some recovery during shutdowns

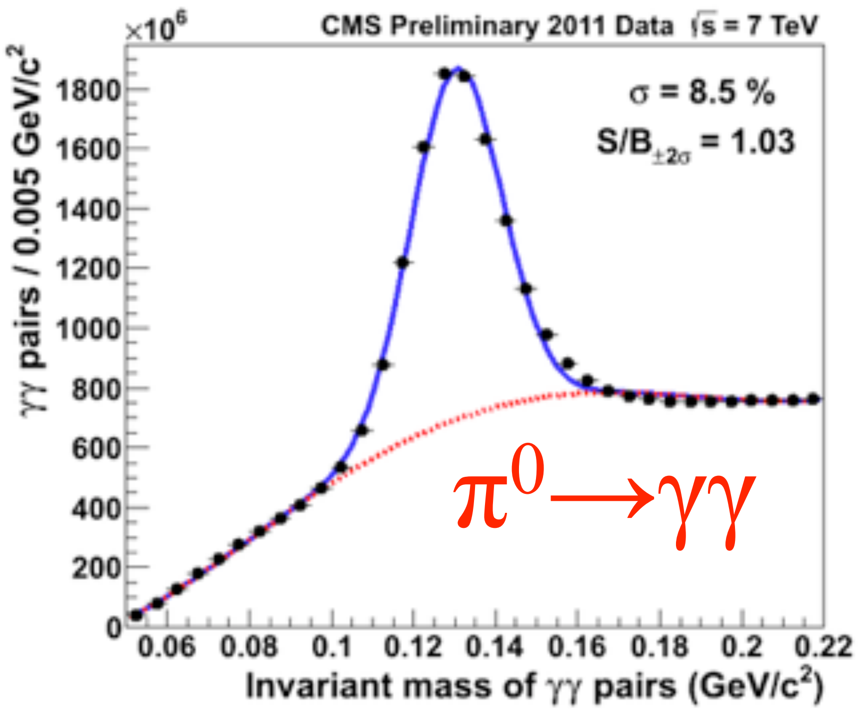


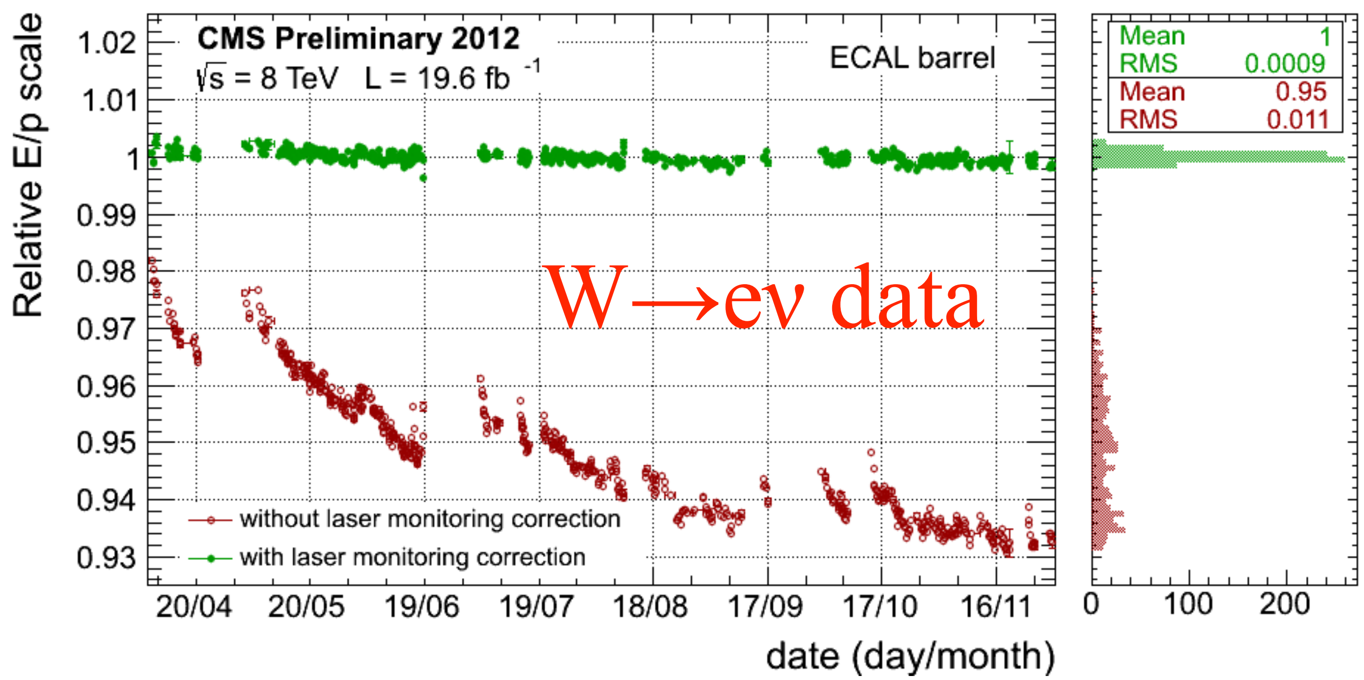


- Require constant calibration and monitoring using standard candles, such as $\pi^0 \to \gamma\gamma$, $Z \to ee$, $Z \to \mu\mu\gamma$ etc.

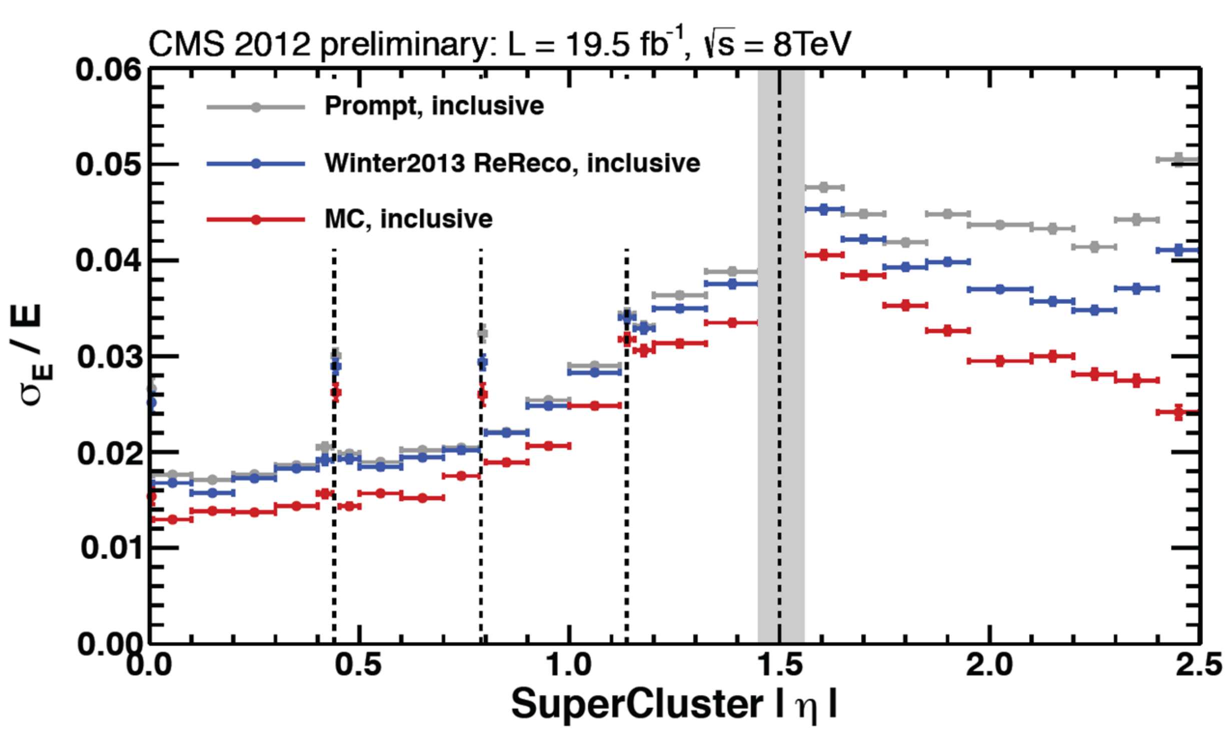


EM Energy scale/resolution

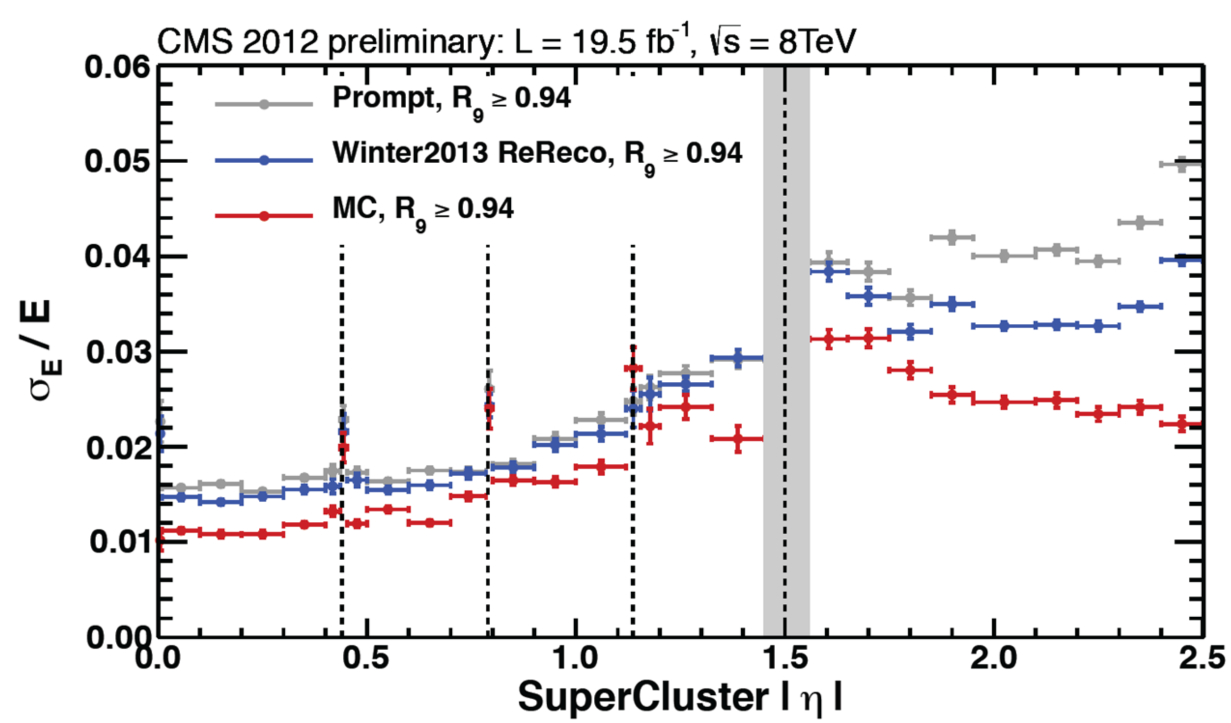




- Resolution obtained from Z→ee data and MC events



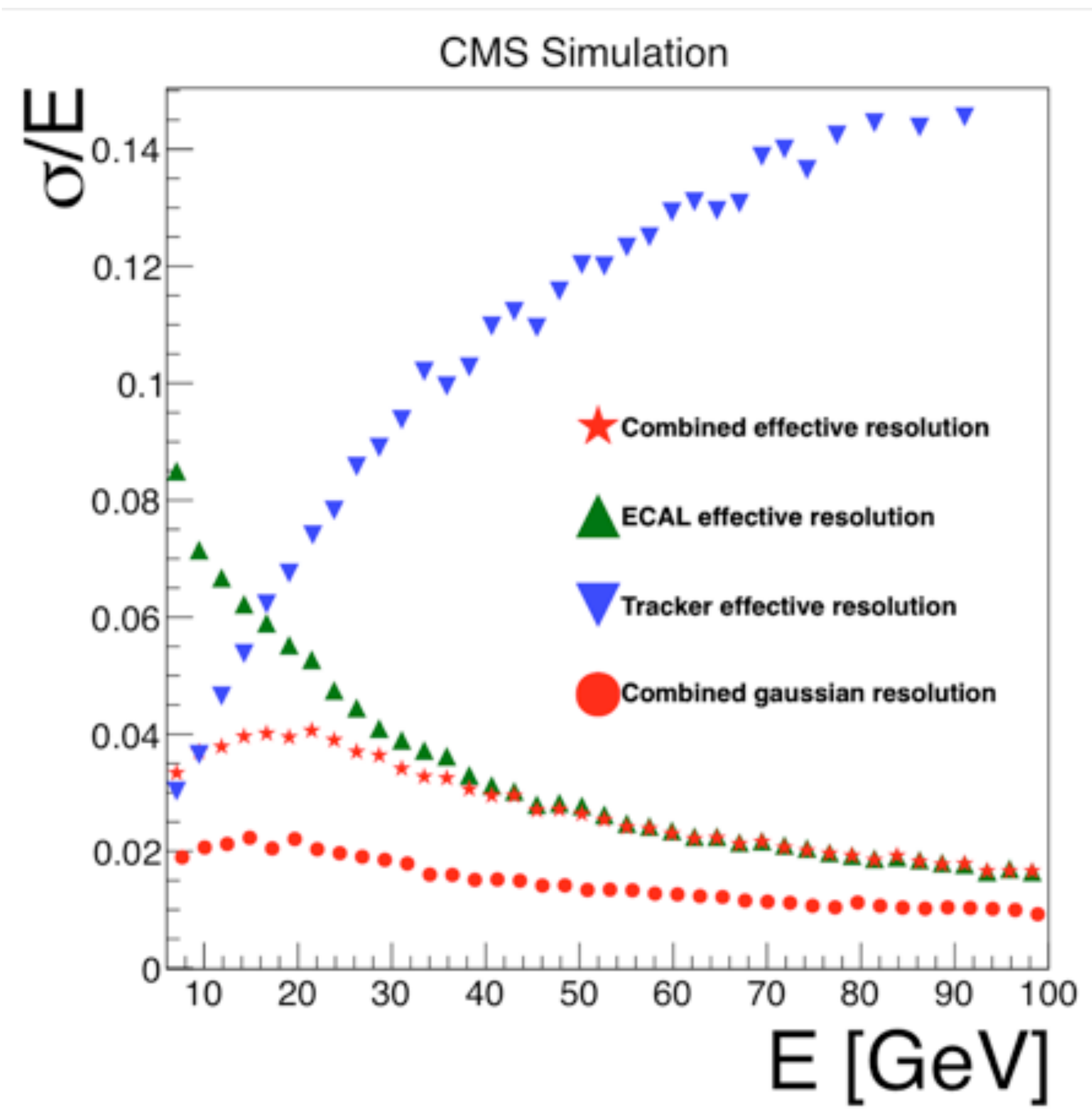
All electrons

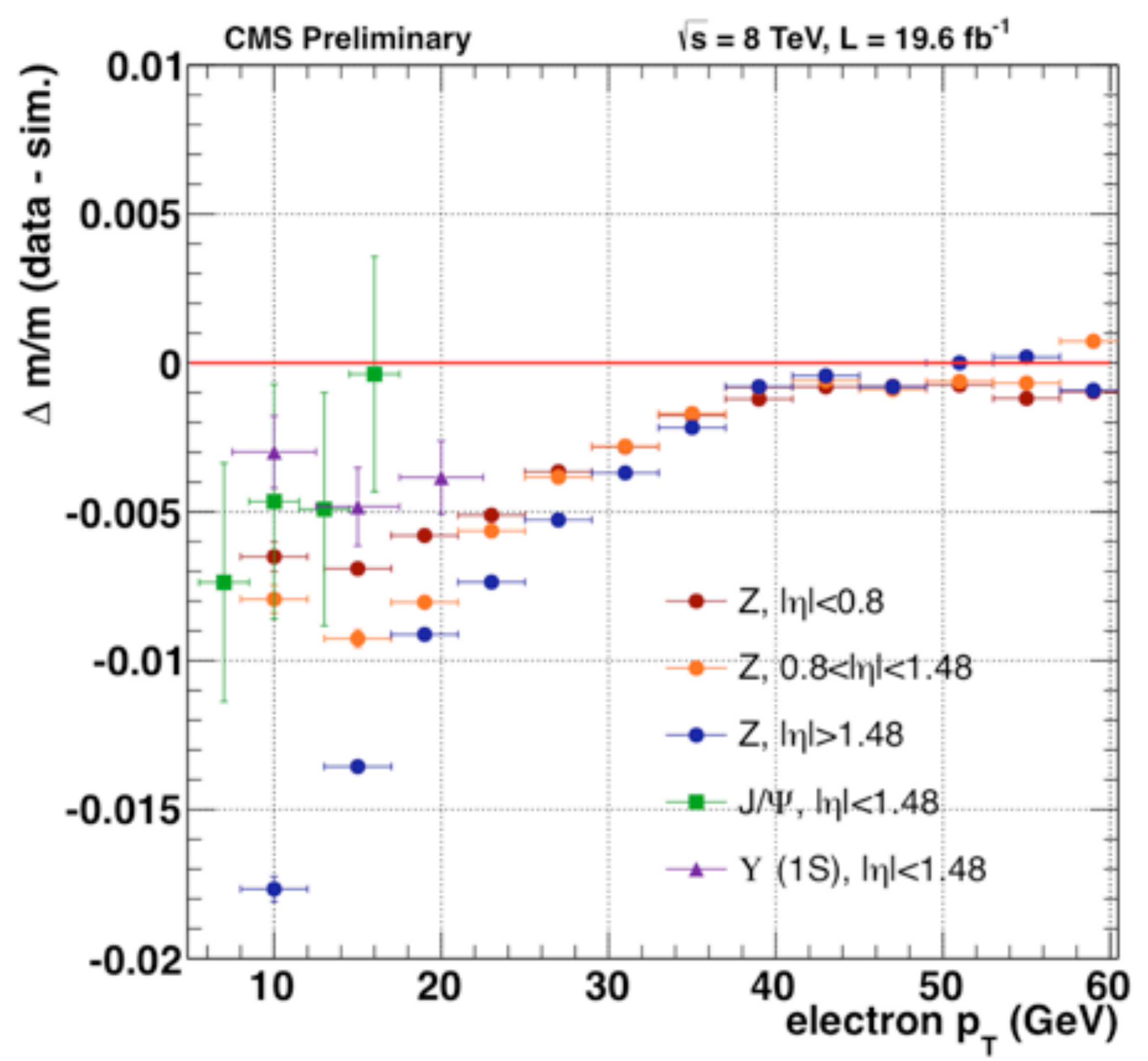


"Golden" ones (not much showering)

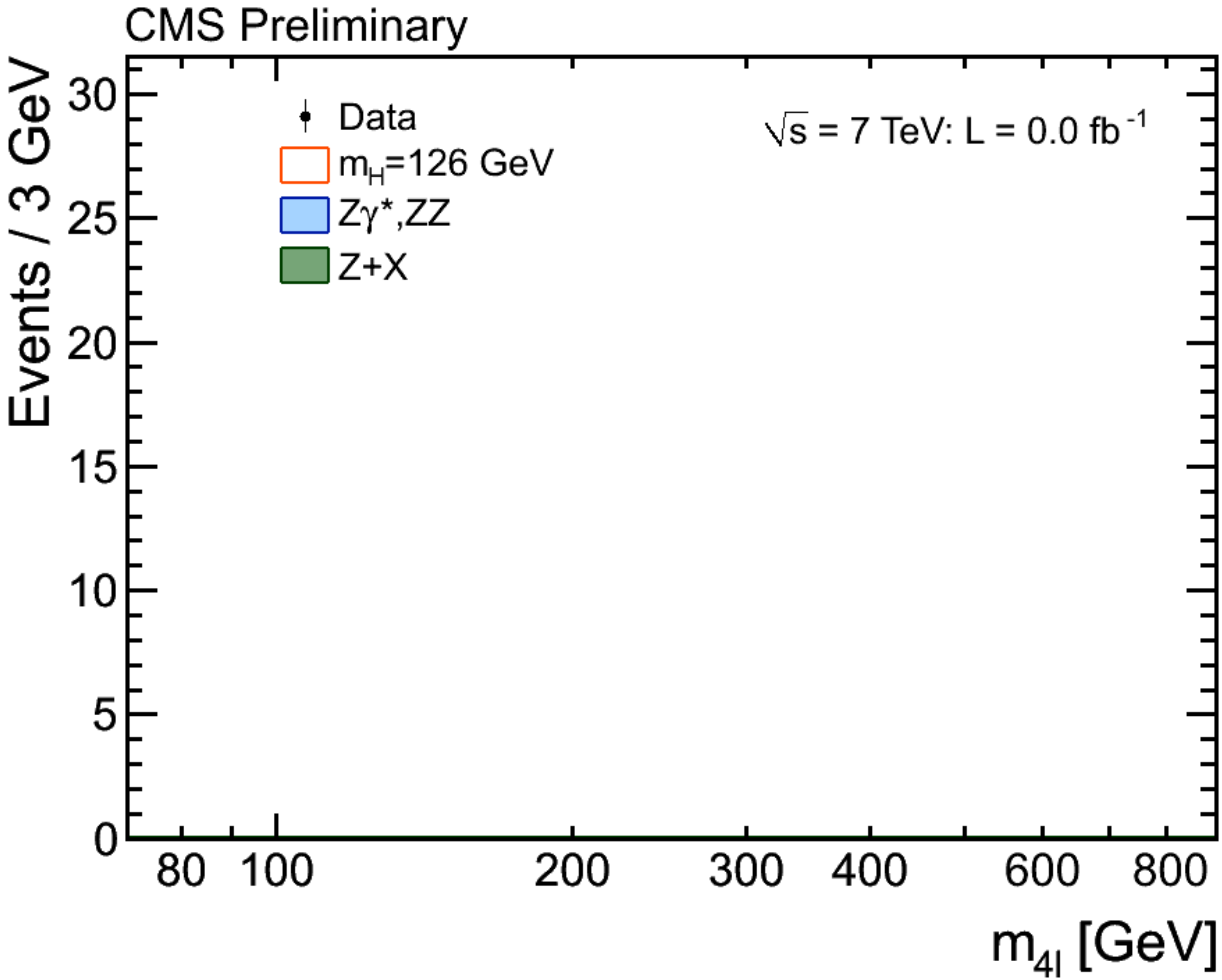
Low energy regime

- For H→ZZ analysis we use both Z and low-mass resonances to cross-check the energy scale
  - Energy scale is well-established within resolution

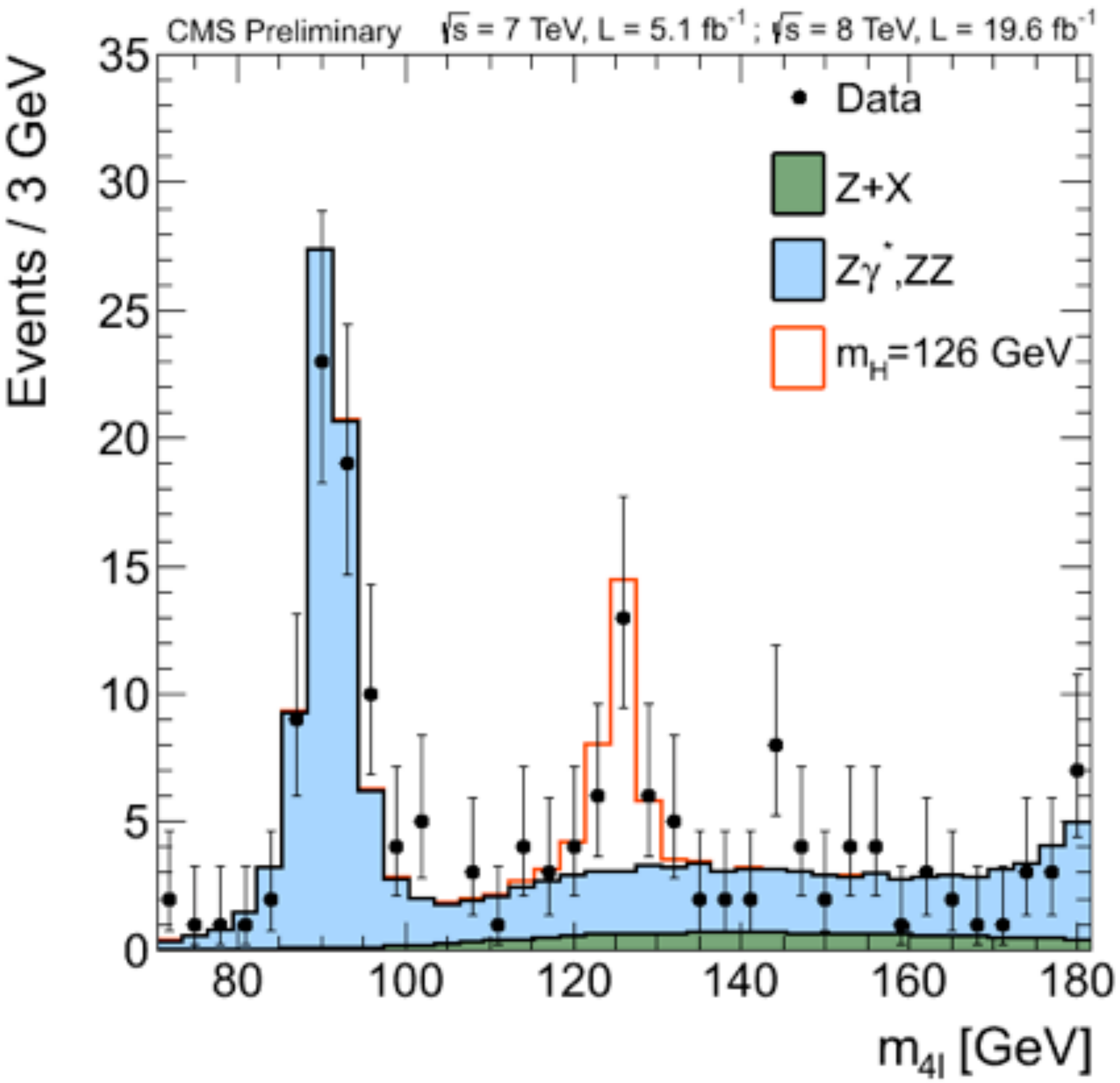


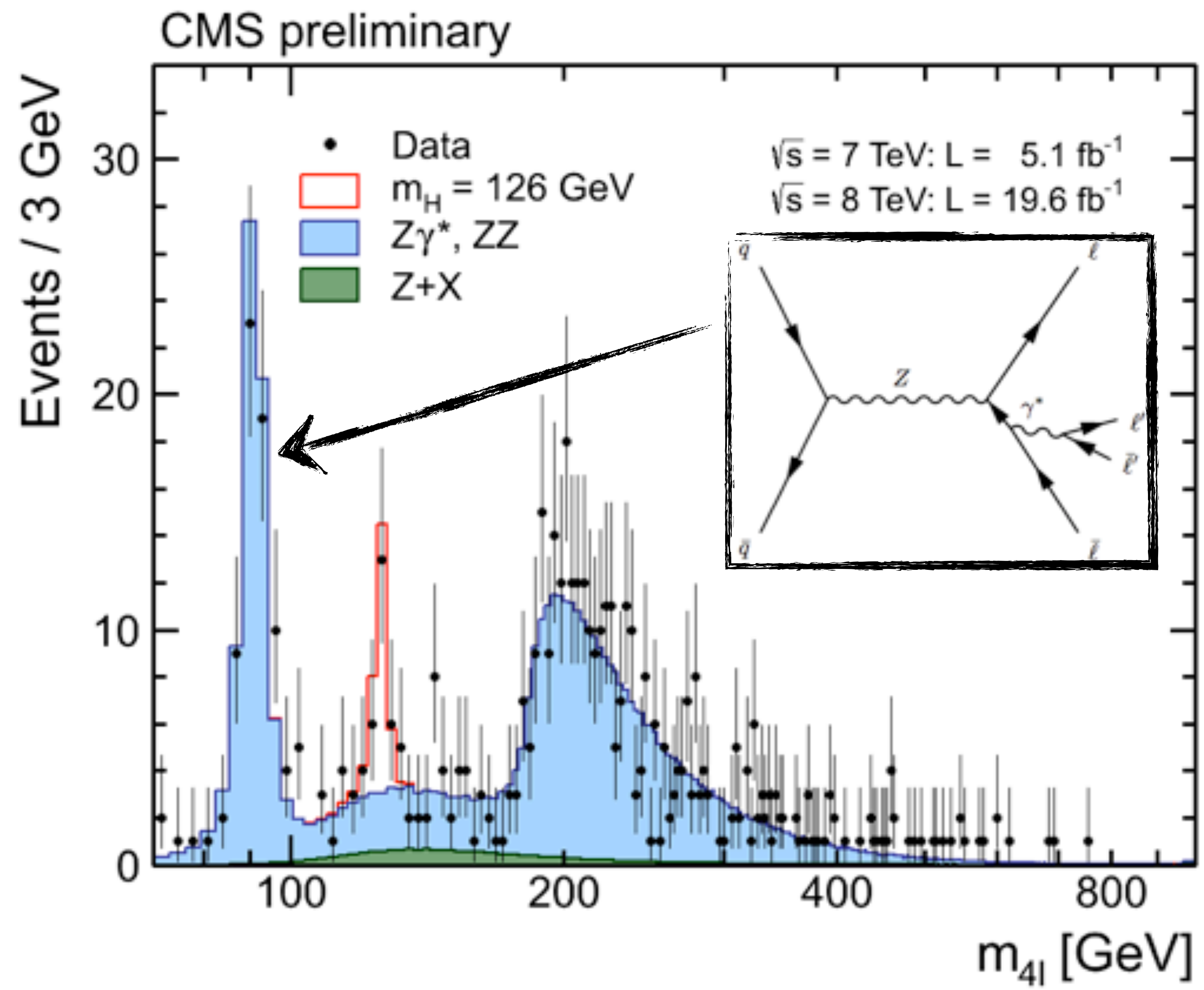


$M_{4\ell}$ distribution



M4ℓ distribution

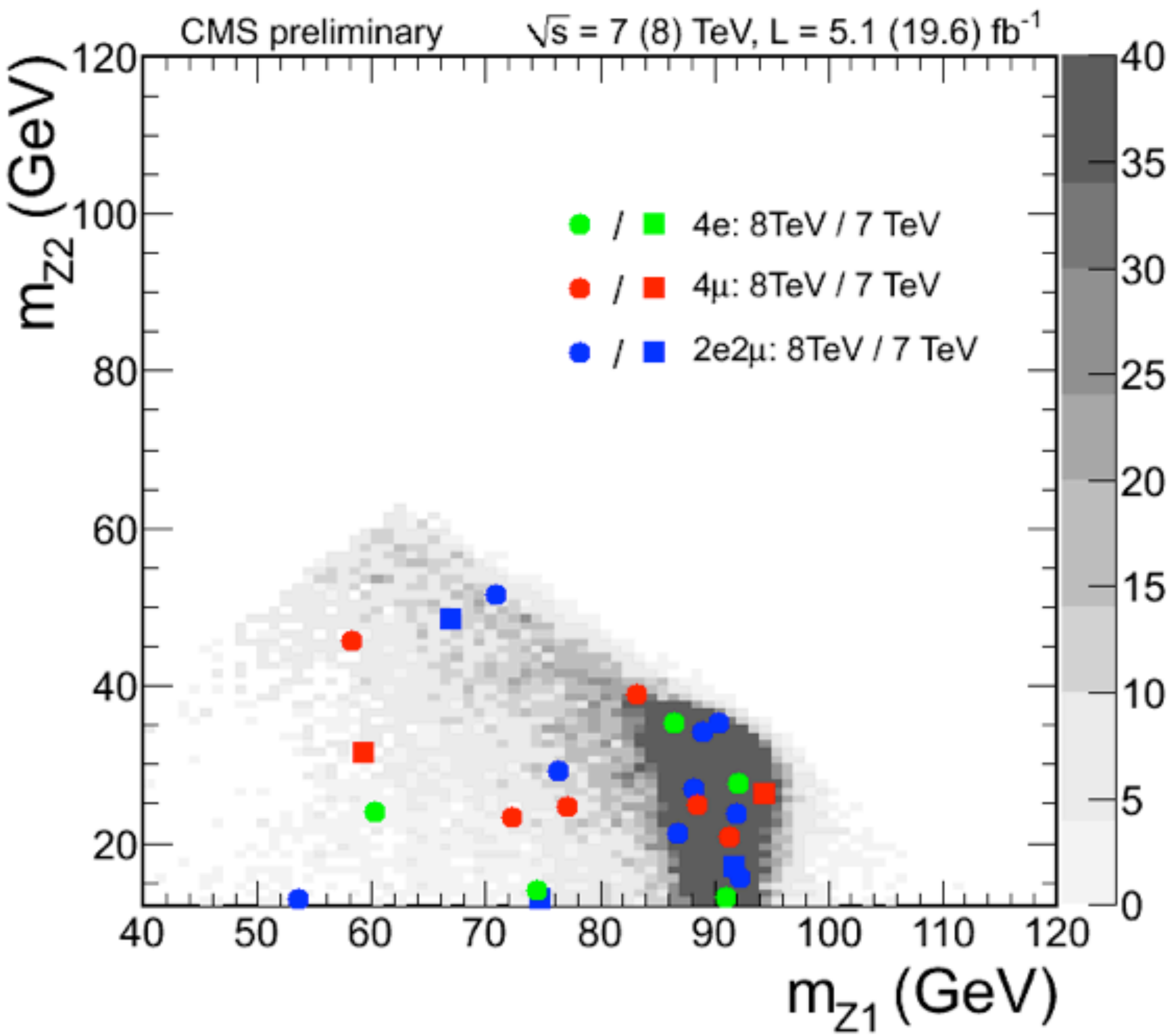




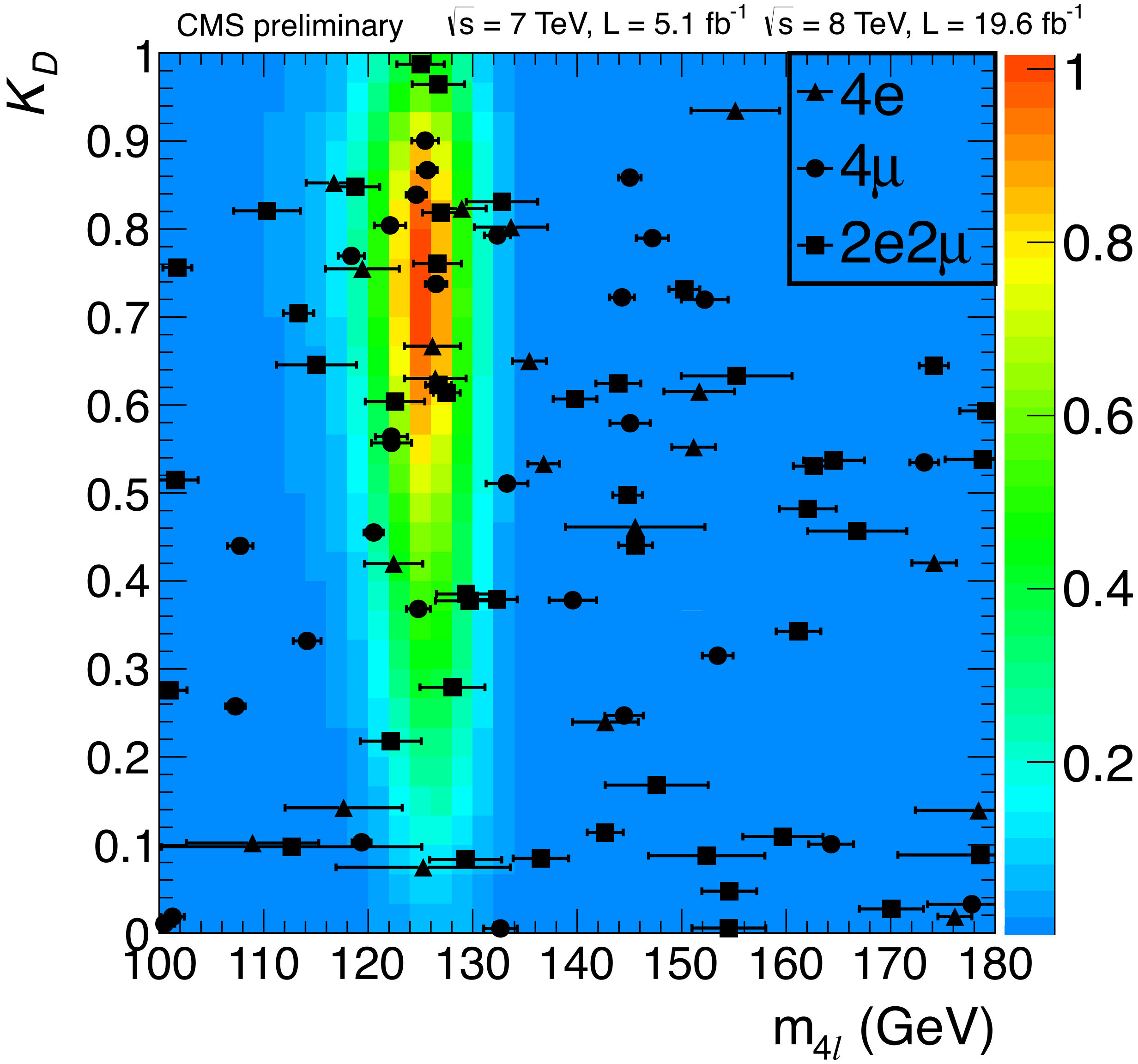
- Good description of the ZZ continuum (and Zγ)
- H→ZZ peak is clearly visible at ~126 GeV
  - One can use kinematics to separate signal from background more!

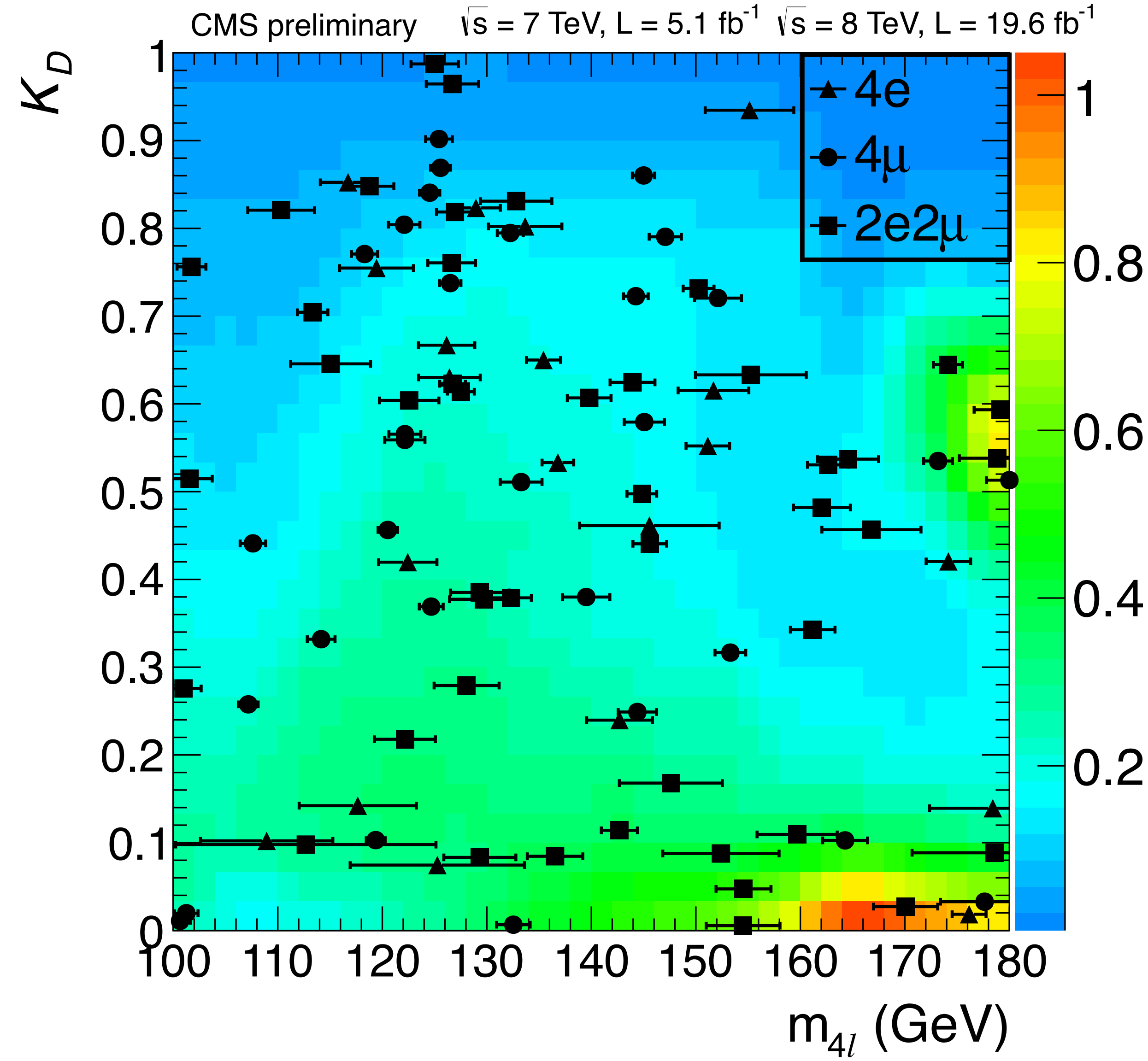
M_{Z1} vs M_{Z2}

- Z_1 vs Z_2 masses for $121.5 < M_{4\ell} < 130.5$ GeV
  - Z_1: OS/SF nearest to the Z boson mass in $40 < M_{Z1} < 120$ GeV
  - Z_2: OS/SF with the highest sum p_T with $12 < M_{Z2} < 120$ GeV



Kinematic discriminant K_D



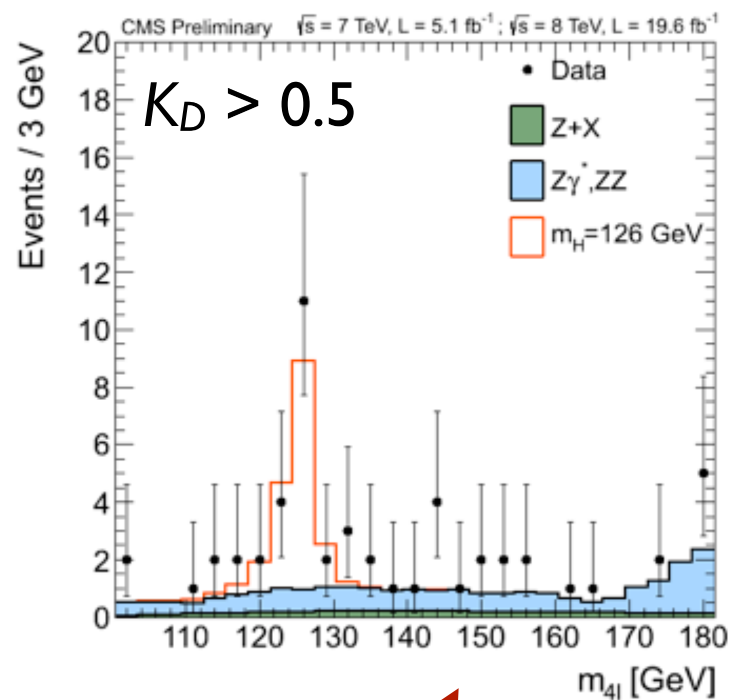


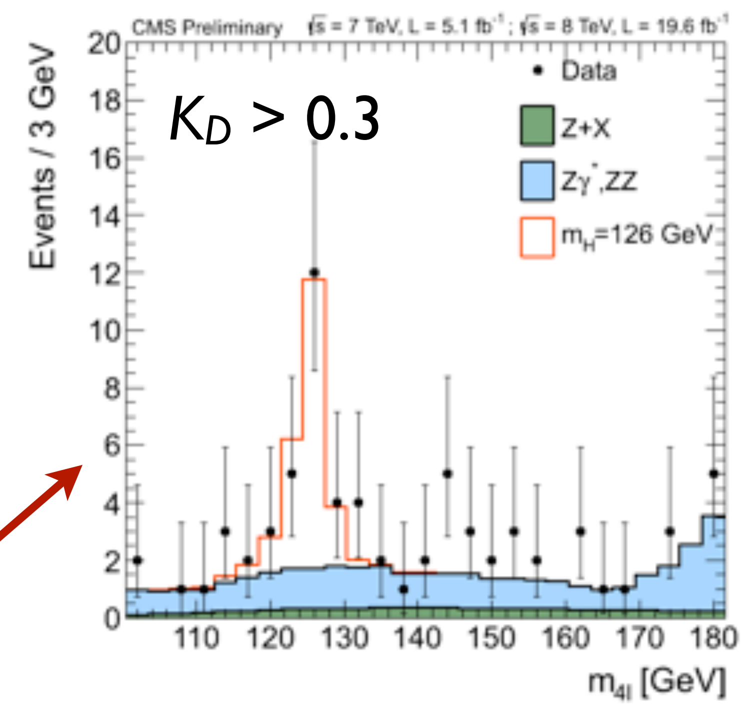
- Function of several kinematic observables

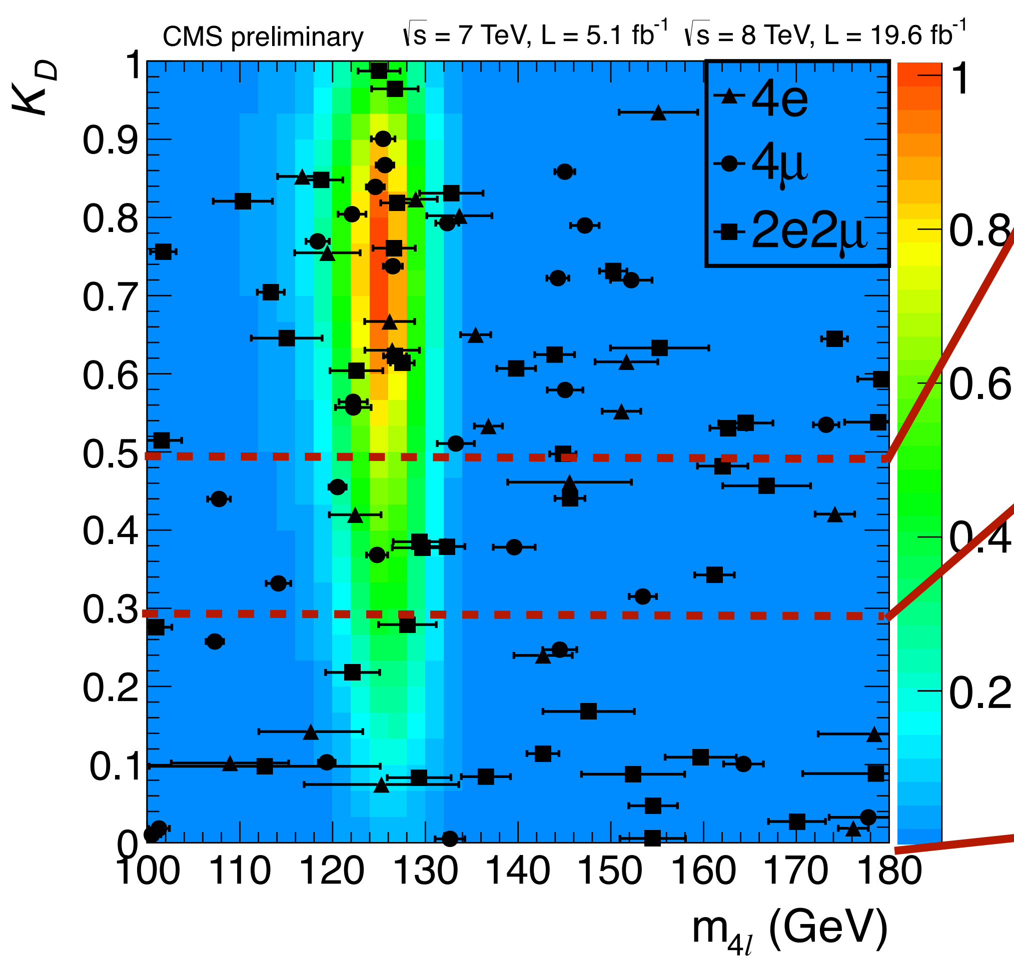
$$K_D(\theta^*, \phi_1, \theta_1, \theta_2, \phi, m_{Z_1}, m_{Z_2}) = \frac{\mathcal{P}_{sig}}{\mathcal{P}_{sig} + \mathcal{P}_{bkg}}$$

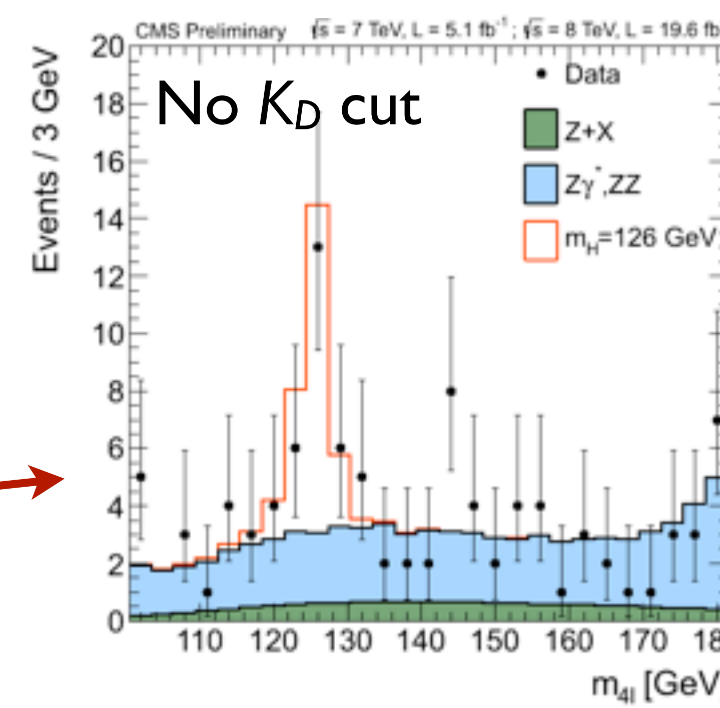
  - BDT, NN etc. offer similar performance (updates with these methods are planned for past-Moriond time)

$M_{4\ell}$ with K_D requirements



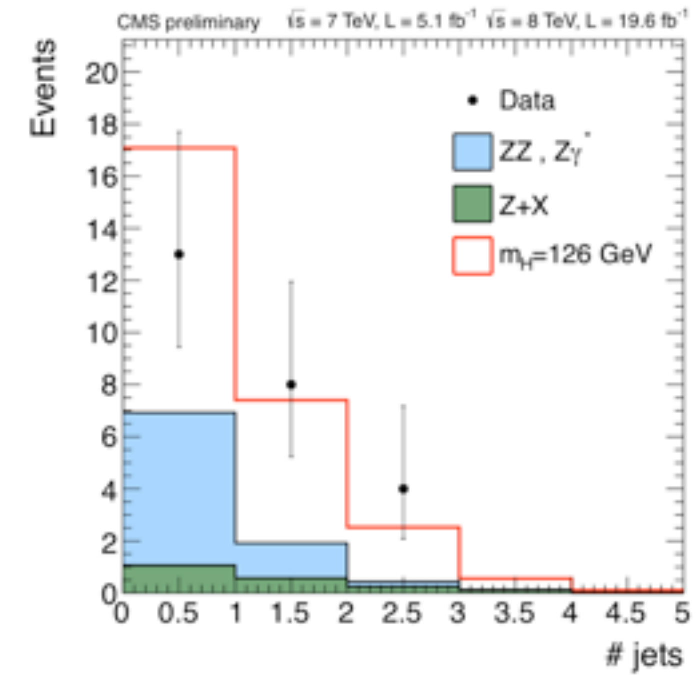


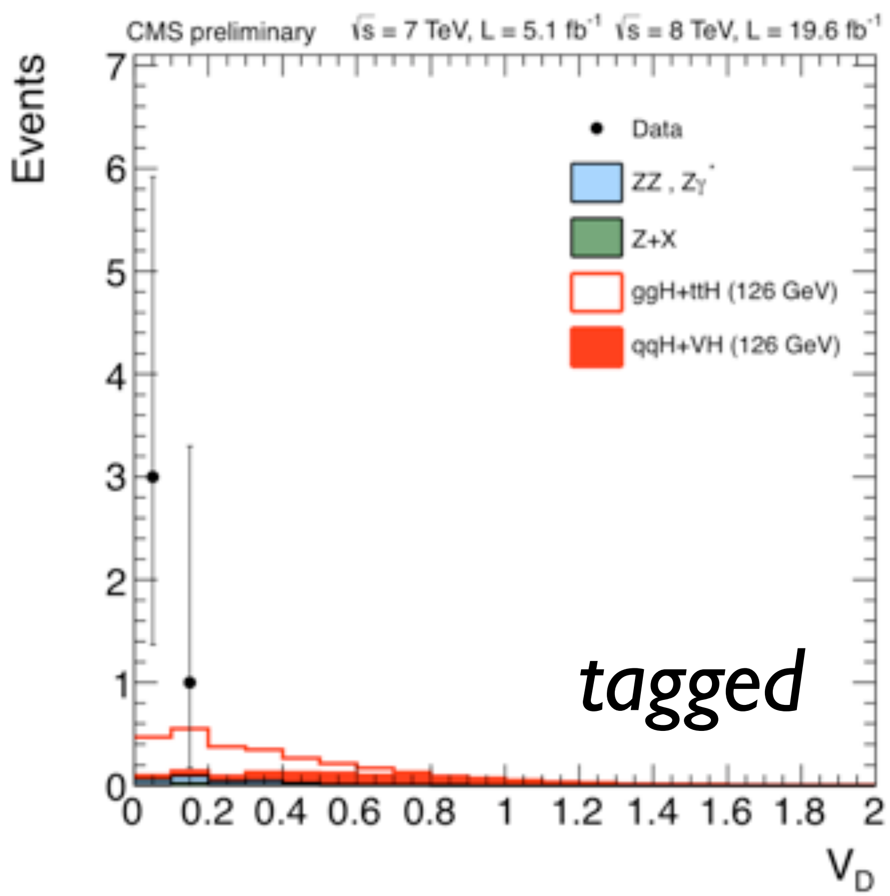


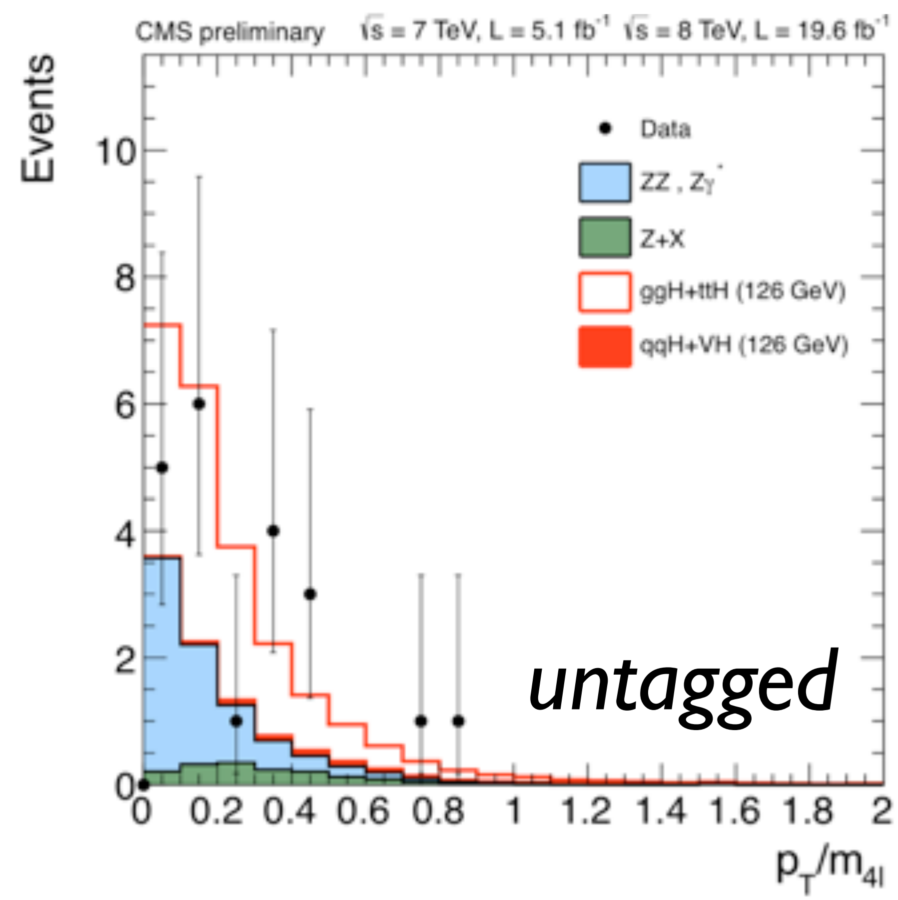


VBF $H \to ZZ$ analysis

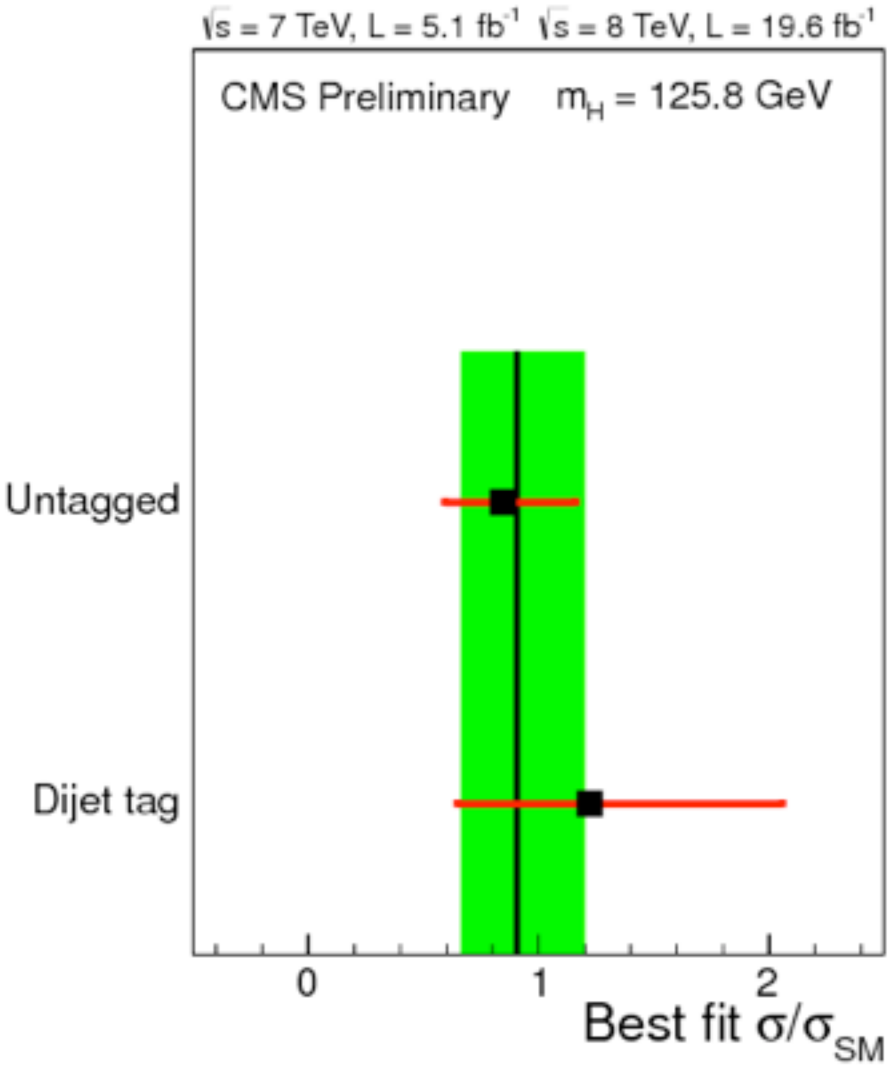
- Sensitivity to VVH and ffH couplings ($\mu_V - \mu_F$)
- Split $121.5 < M_{4\ell} < 130.5$ GeV events into two categories
  - Tagged: events with ≥ 2 jets ($p_T > 30$ GeV, $|\eta| < 4.7$)
    - Use Fisher discriminant with m_{jj} and $\Delta\eta_{jj}$ as inputs
  - Untagged: all other events
    - Use $p_T/m_{4\ell}$ as discriminant

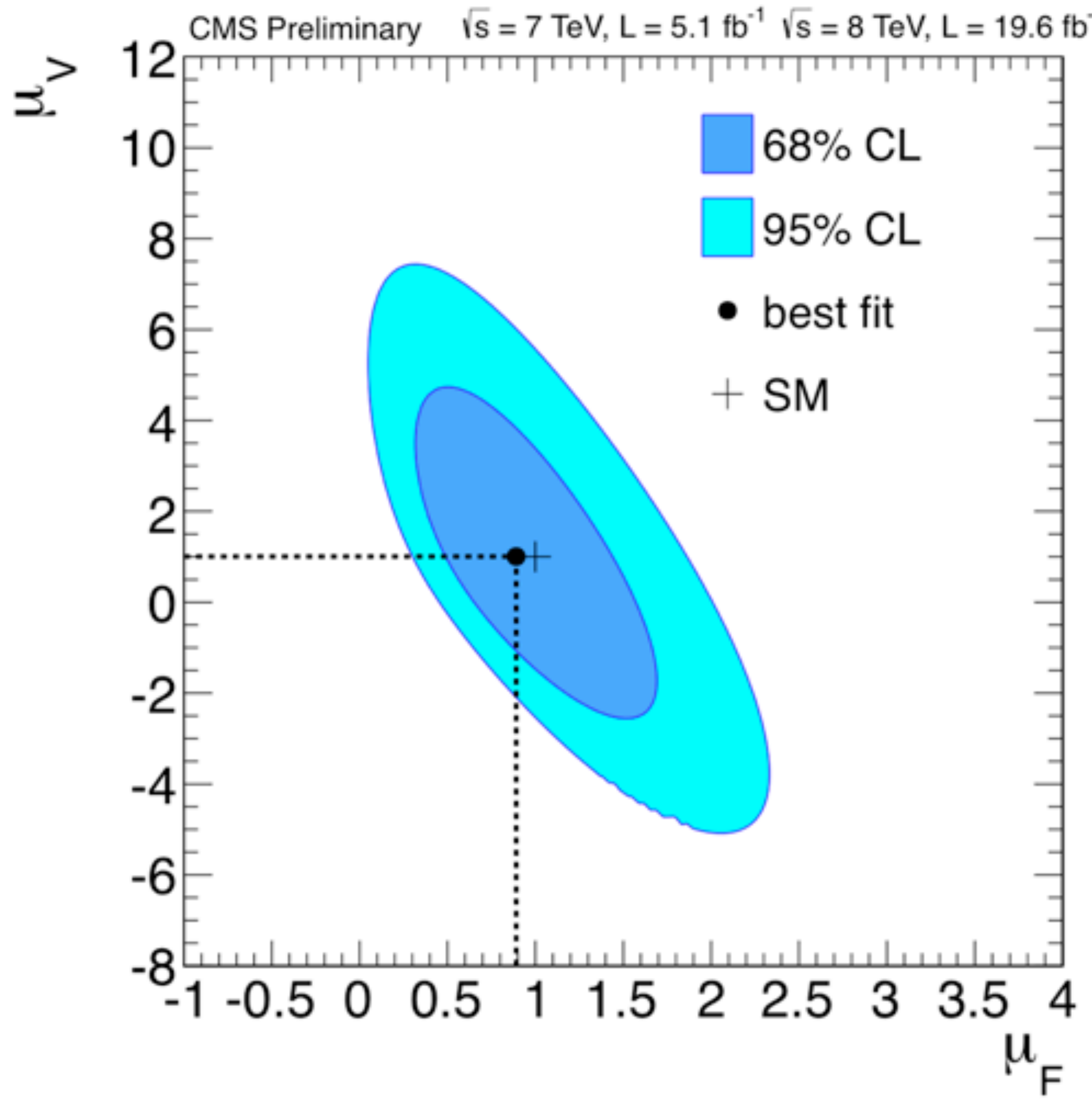






Production mechanism





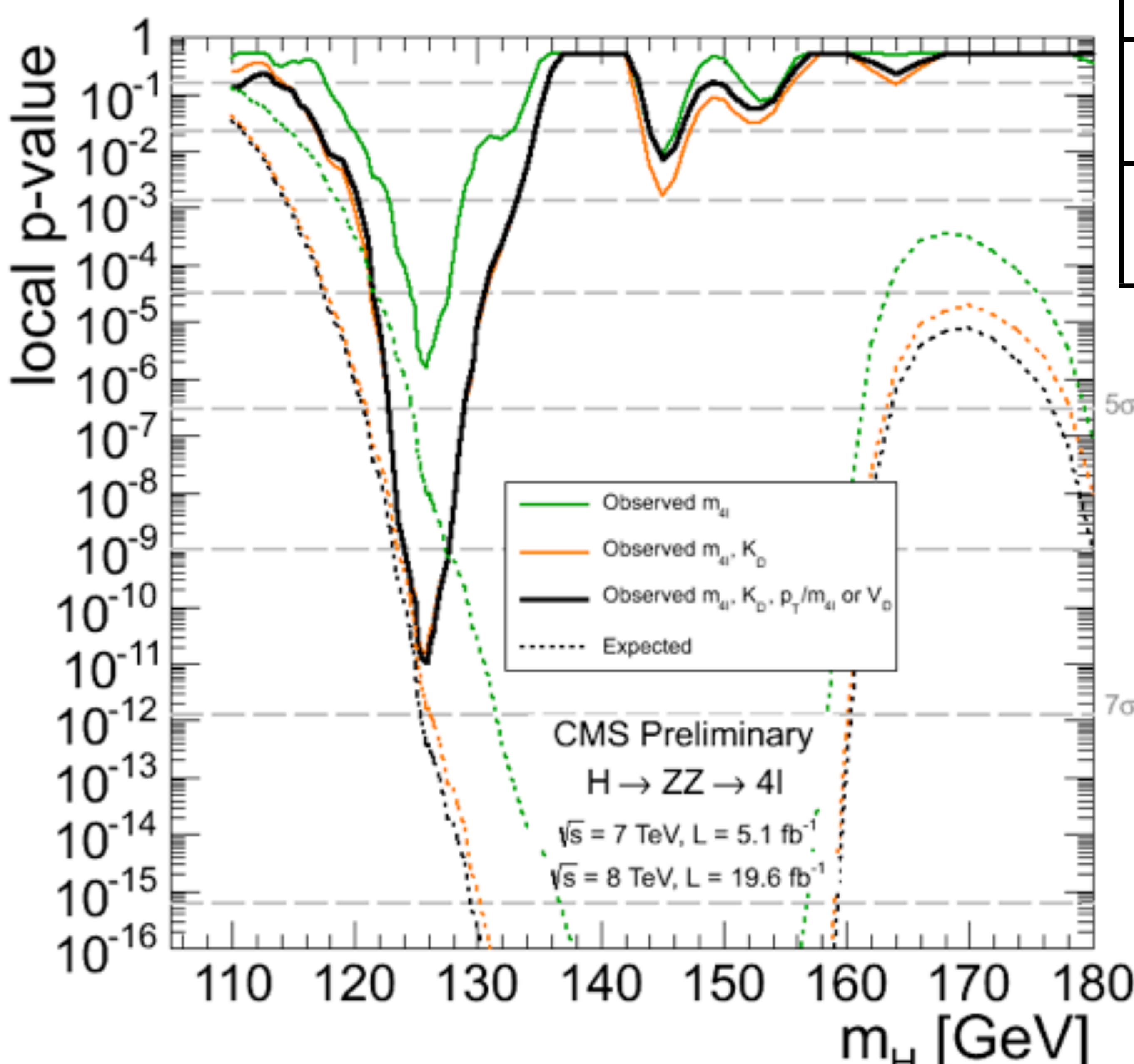
$$\sigma/\sigma_{\mathrm{SM}} = 0.91^{+0.30}_{-0.24}$$

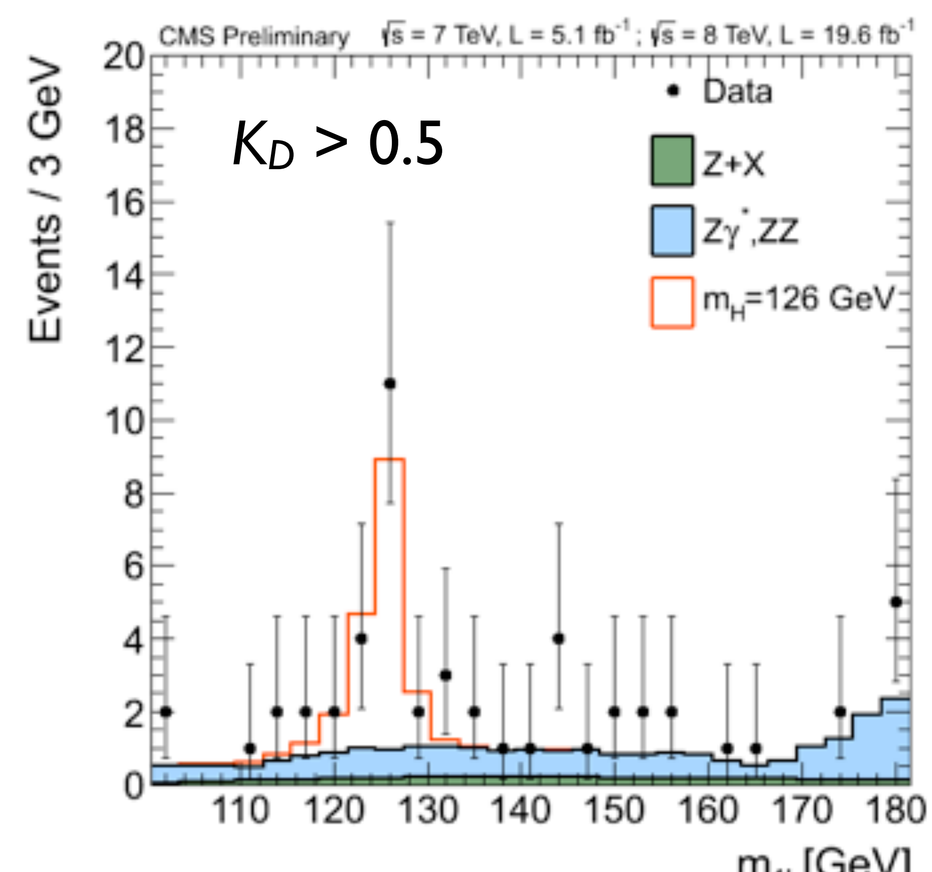
$$\mu_V(qq\mathrm{H},\ \mathrm{ZH},\ \mathrm{WH}) = 1.0^{+2.4}_{-2.3}$$
$$\mu_F(gg \to \mathrm{H},\ t\bar{t}\mathrm{H}) = 0.9^{+0.5}_{-0.4}$$

Sensitivity

- Minimum *p*-value is at low mass ~125.8 GeV
- More than 5σ significance

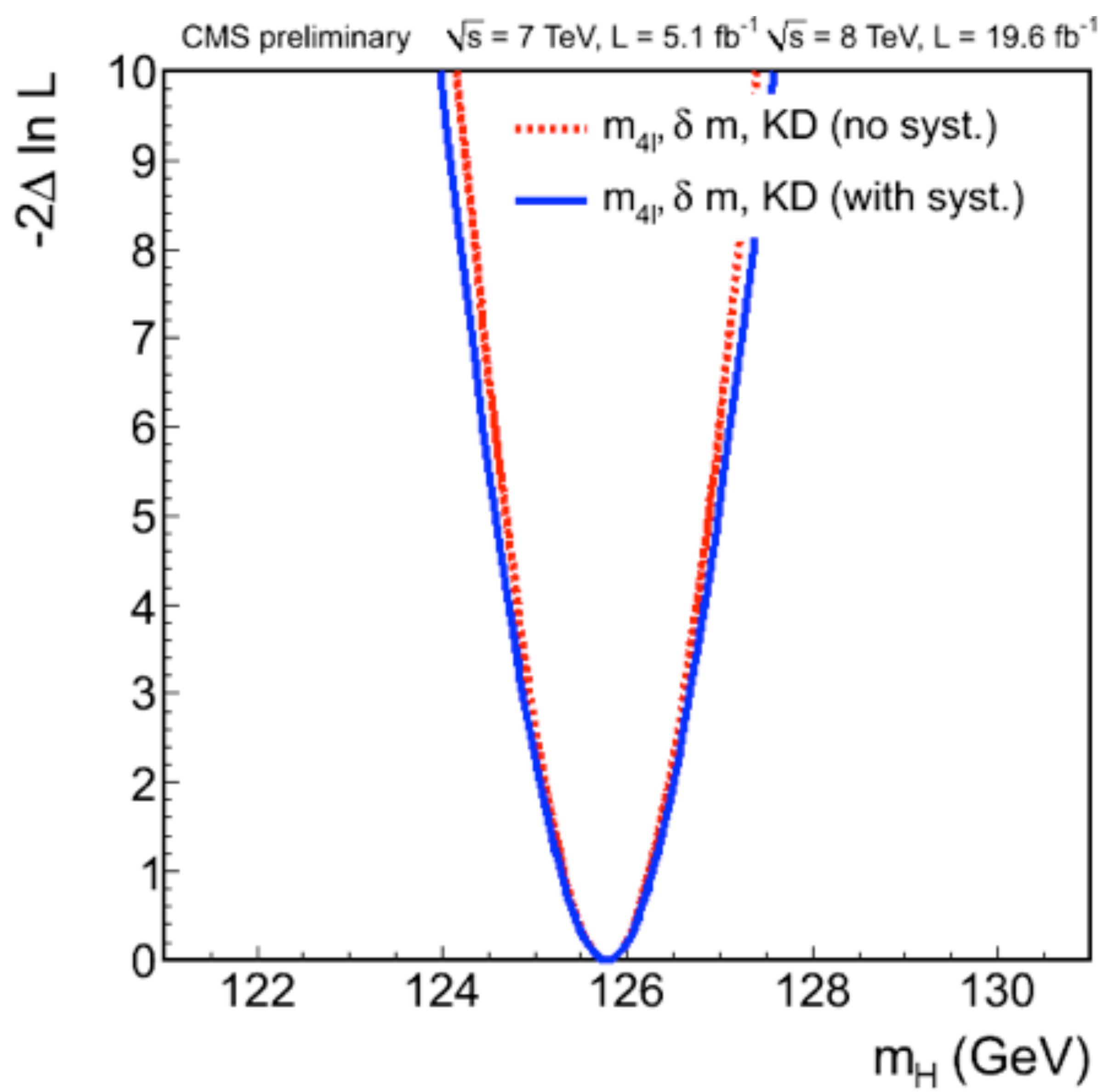
Analysis	Expected	Observed
1D($m_{4\ell}$)	5.6σ	4.7σ
2D($m_{4\ell}$, K_D)	6.9σ	6.6σ
3D($m_{4\ell}$, K_D, V_D–$p_T/m_{4\ell}$)	7.2σ	6.7σ





H→ZZ→4ℓ mass measurement

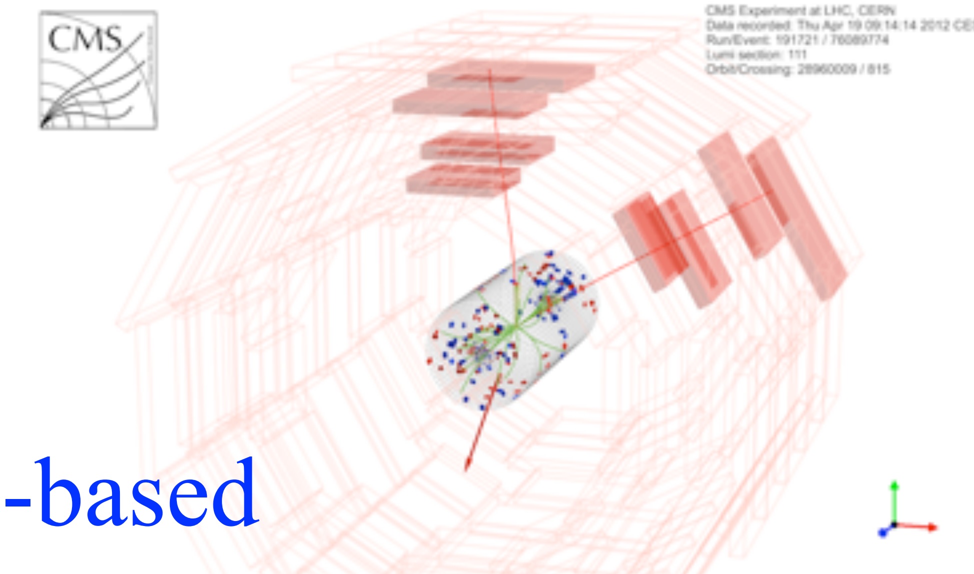
- Use lepton momentum uncertainties to build event-by-event mass uncertainty
  - Result: $m_{\mathrm{H}} = 125.8 \pm 0.5(\mathrm{stat.}) \pm 0.2(\mathrm{syst.})$ GeV
    - Still statistically limited



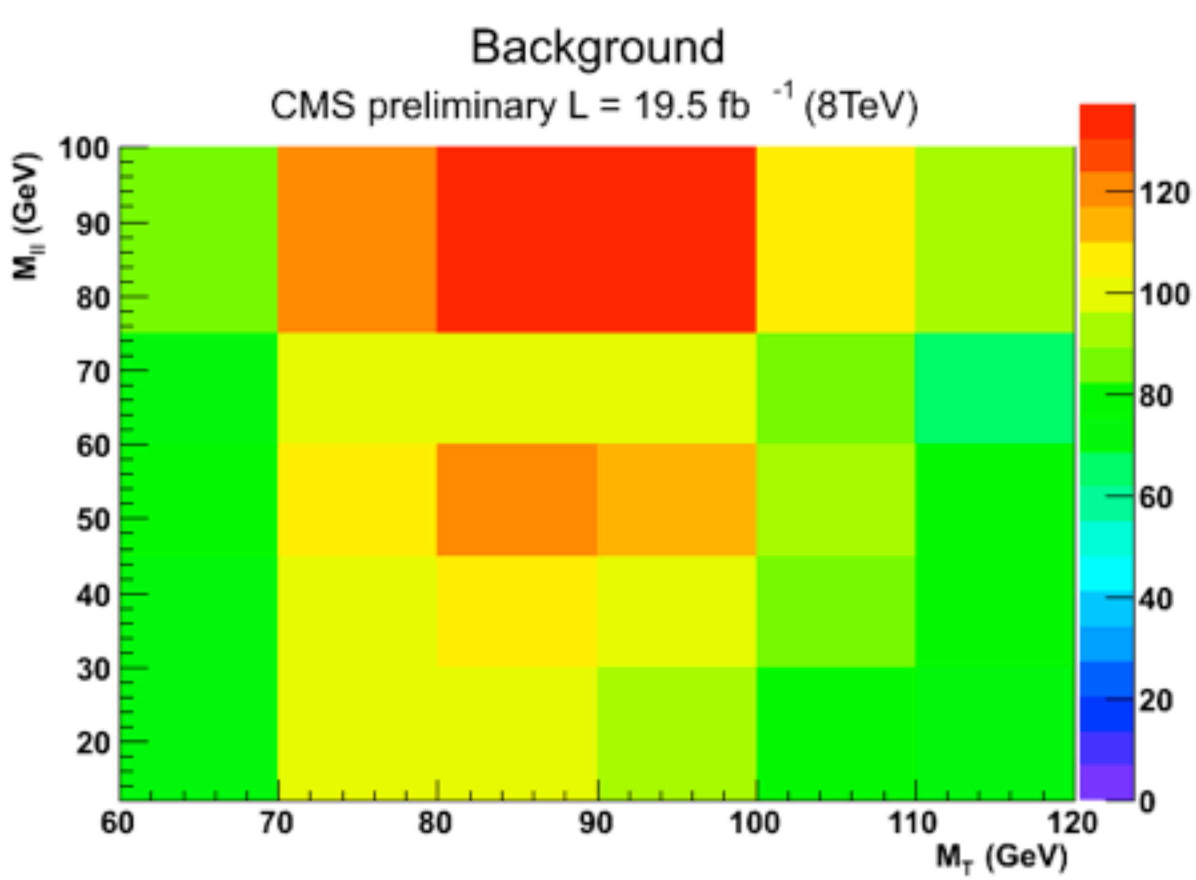
$H \to WW \to 2\ell 2\nu$

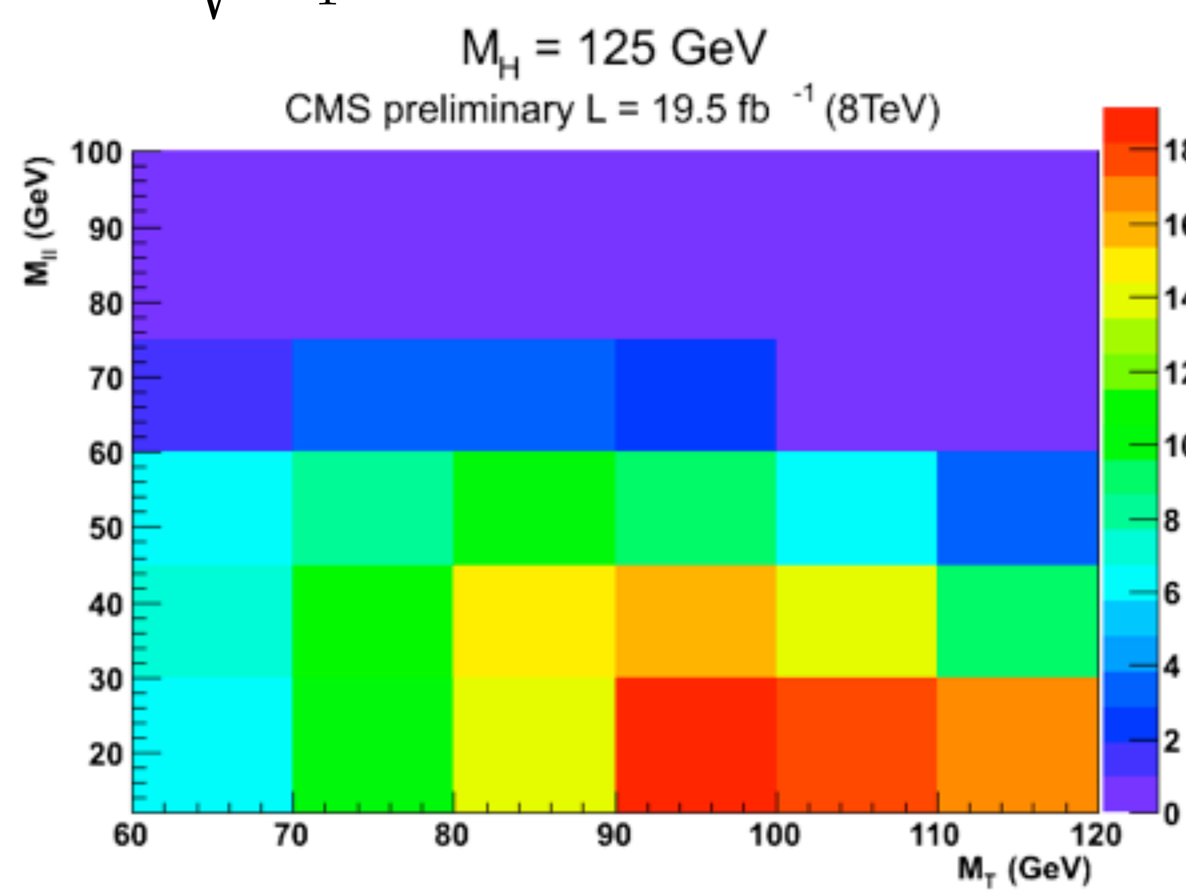
HIG-13-003

- Two high-p_T isolated leptons and moderate MET



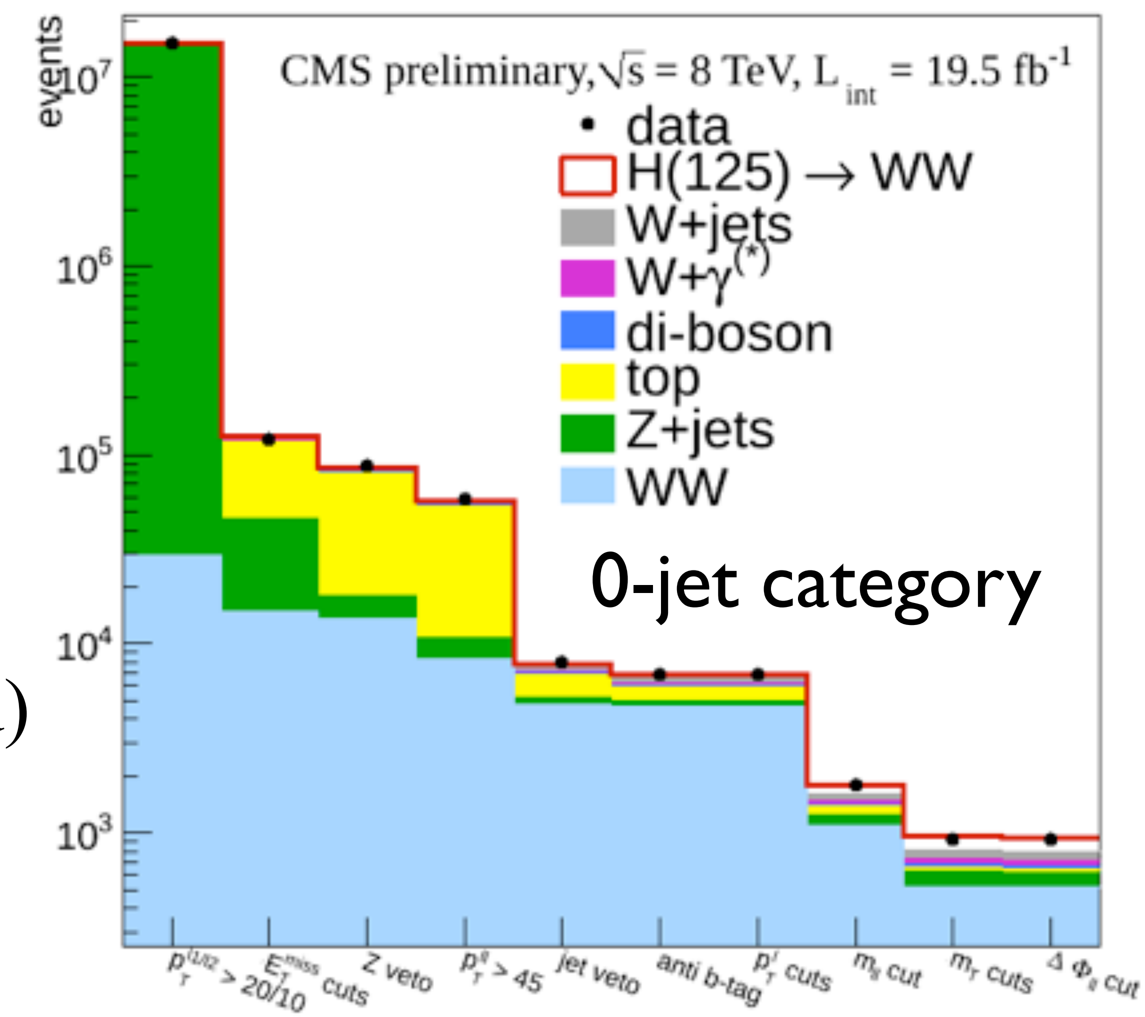
- Split data into two categories
  - different-flavor (DF), same-flavor (SF)
  - No jet, 1-jet (VBF is not updated for Moriond)
- Two approaches: cut-based and shape-based
  - Use 2D ($M_{\ell\ell} - M_T$) to separate signal from background for DF shape-based analyses, counting method for the rest; $M_T = \sqrt{2 p_T^{\ell\ell}\ \mathrm{MET}\ cos\Delta\phi_{\ell\ell-\mathrm{MET}}}$





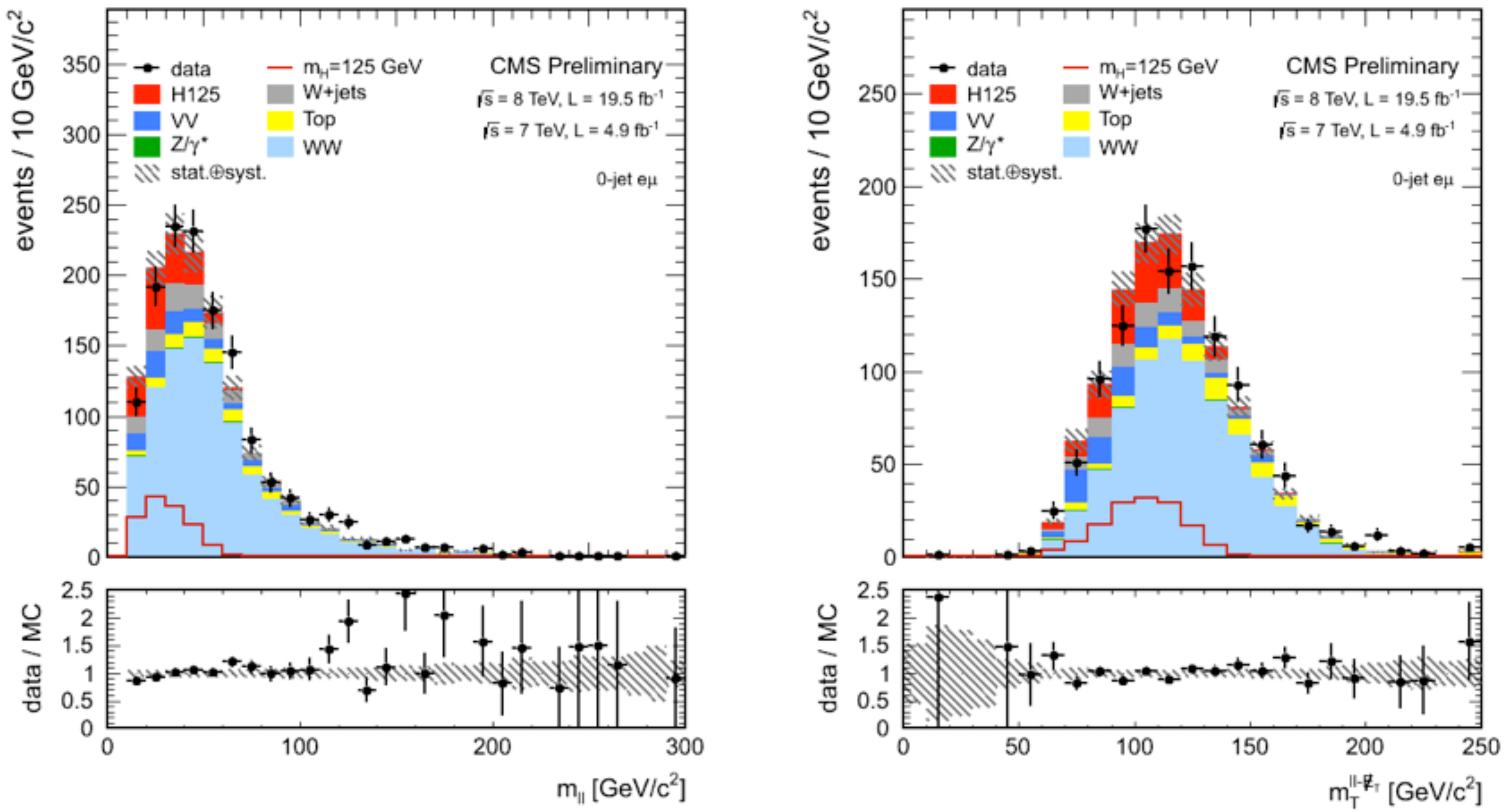
$H \to WW \to 2\ell 2\nu$ backgrounds

- Selection to reduce backgrounds
  - W+Jets: tight lepton identification and isolation
  - Drell-Yan: MET and Z veto in SF category
  - Top: top-veto using b-tagging and soft-muon tagging, as well as jet binning
  - WZ/ZZ: reject events with a third lepton
- All major backgrounds are estimated from data
- Continuum WW production is the dominant background
  - Extract from $M_{\ell\ell}$ control region (cut-based) or free-floating normalization in 2D fit



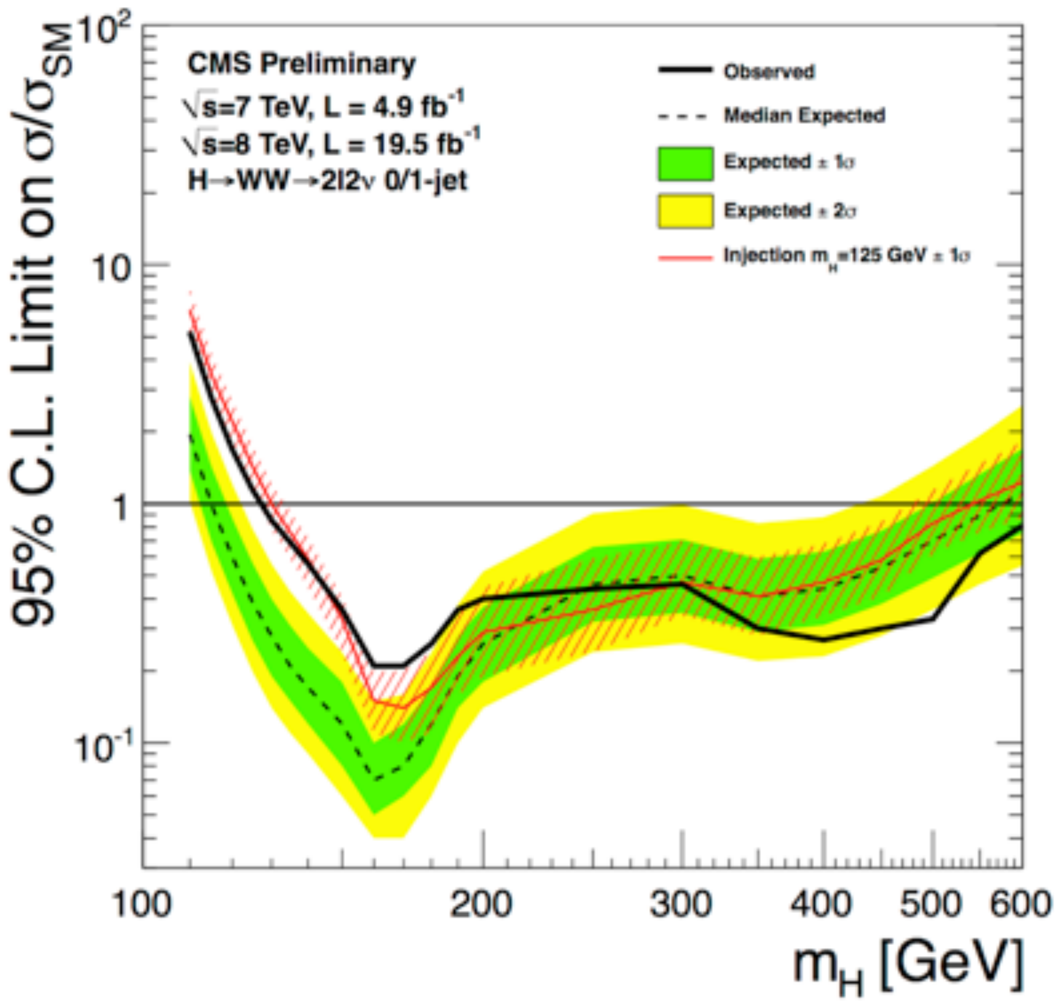
H→WW→2ℓ2ν N-1 distributions

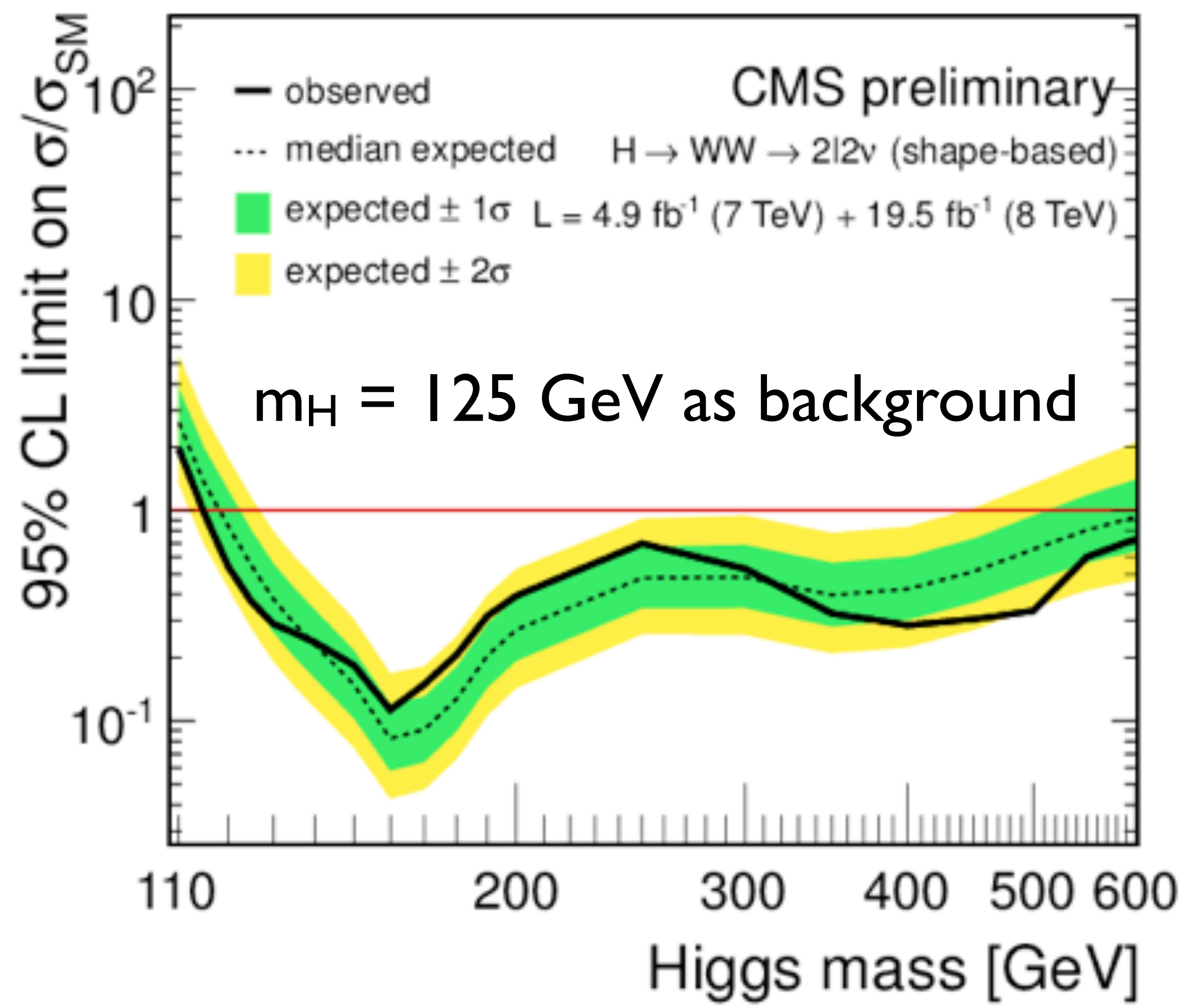
- Different flavor 0-jet category for combined data sets after all selection criteria but one:



  - Relatively large excess for a "simple" cut-based analysis

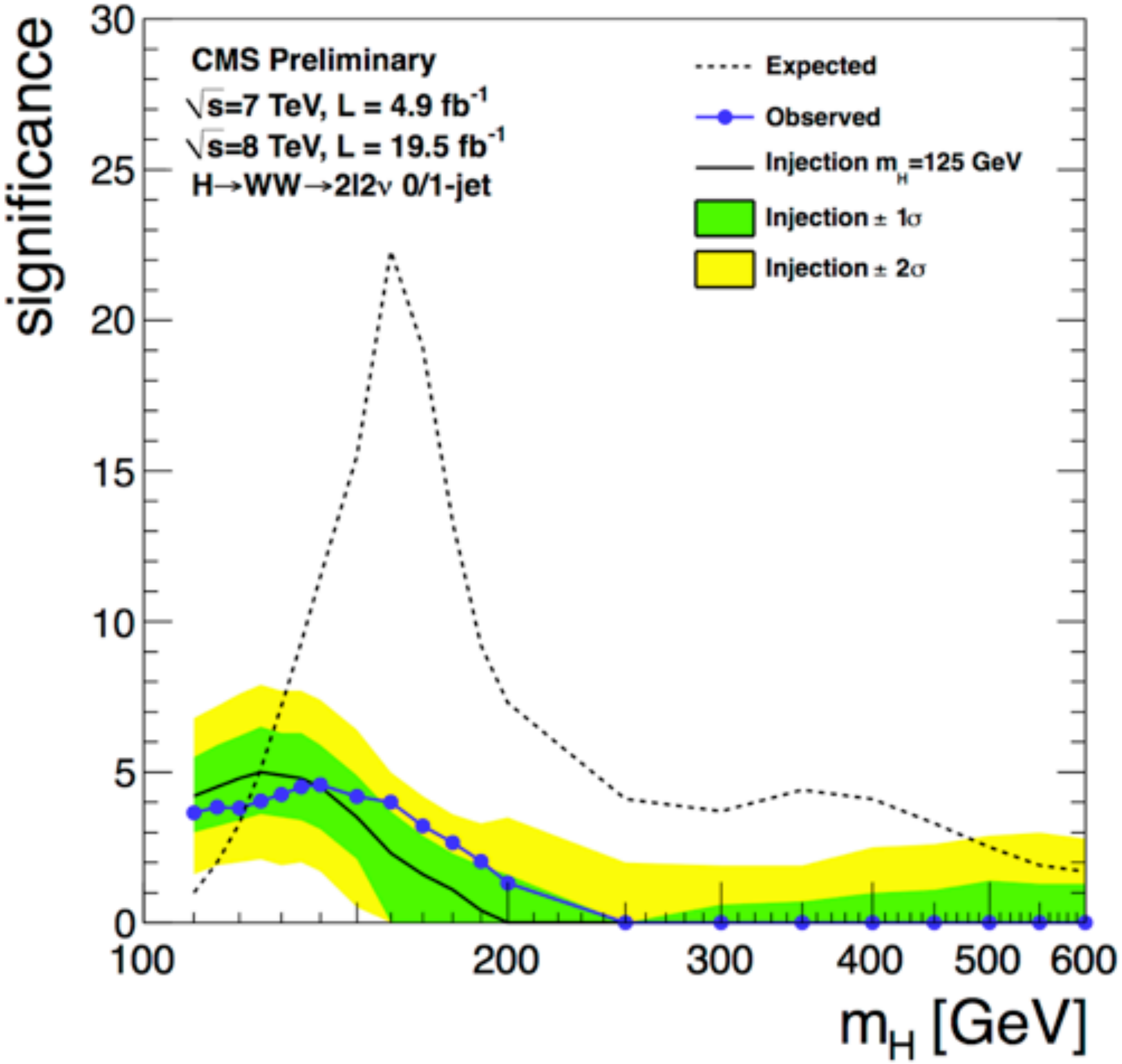
H→WW→2ℓ2ν upper limits

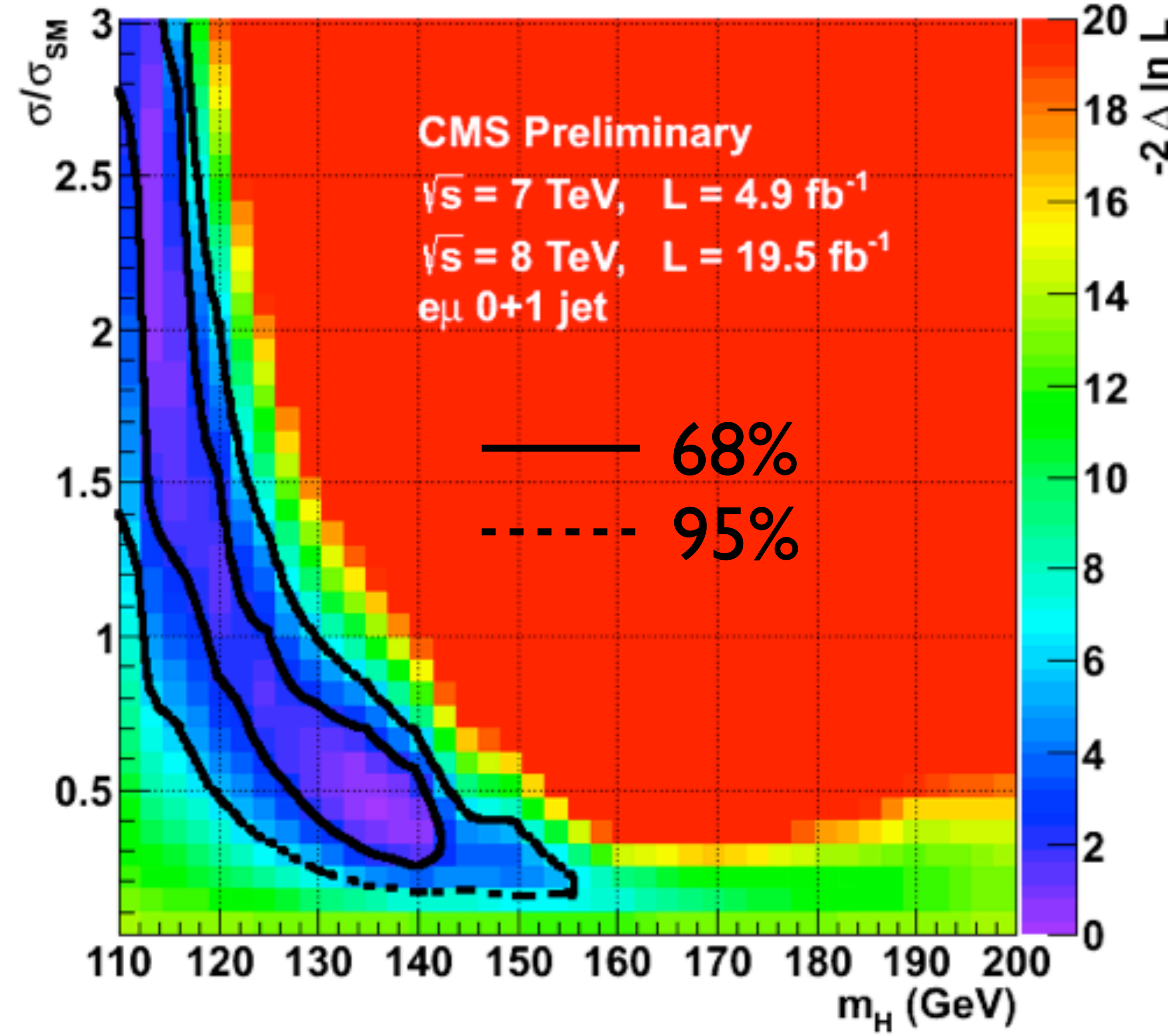




- Exclude 128-600 GeV at 95% C.L.
- Excess in the low mass region results in a weaker than expected upper limit
  - Injecting m_H = 125 GeV signal as the background results in no excess to be observed
  - Consequently, no evidence for other resonances with high mass

$H \to WW \to 2\ell 2\nu$ significance



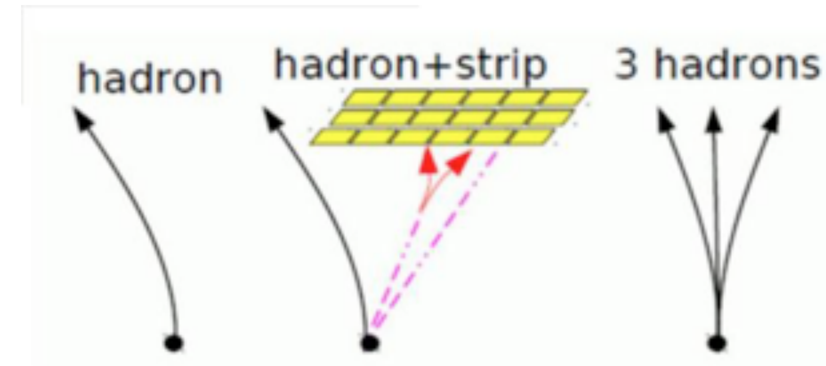


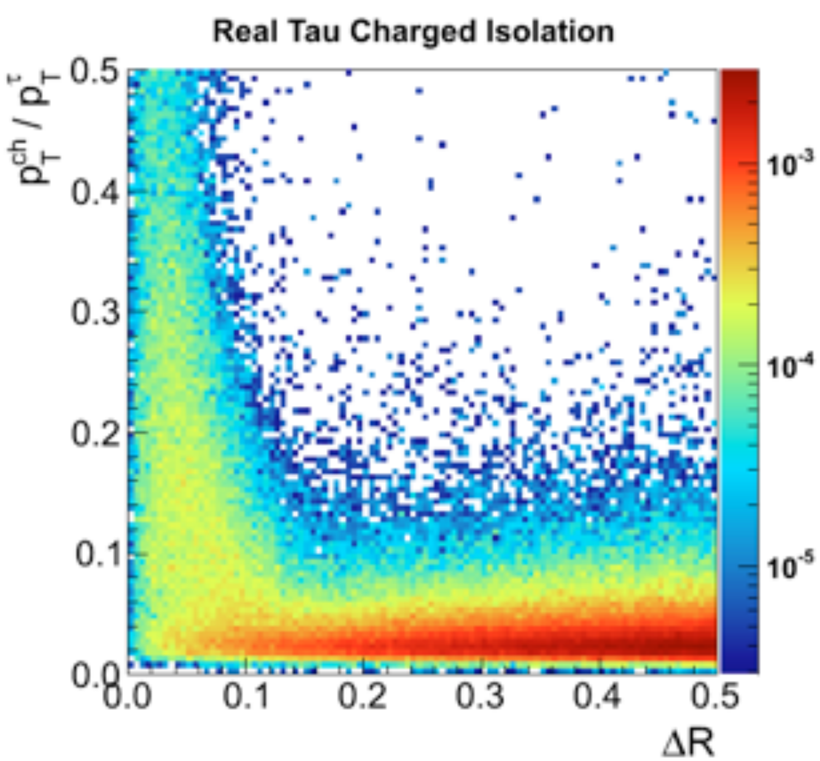
- Observed significance of the excess is 4.0σ, expected is 5.1σ (shape-based analysis)
  - $\sigma/\sigma_{SM} = 0.76 \pm 0.21$

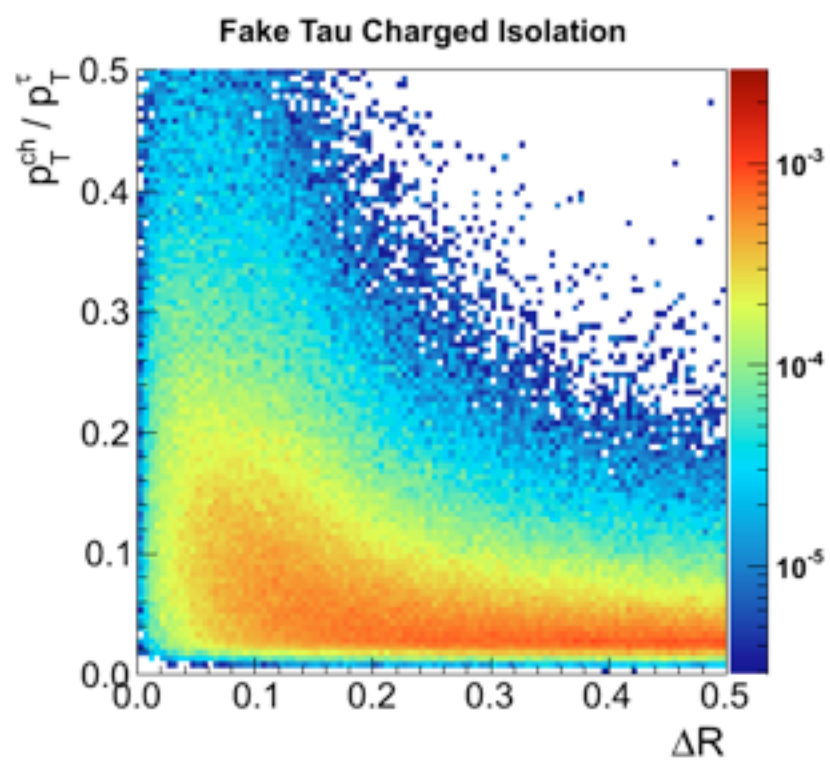
Search for H→ττ

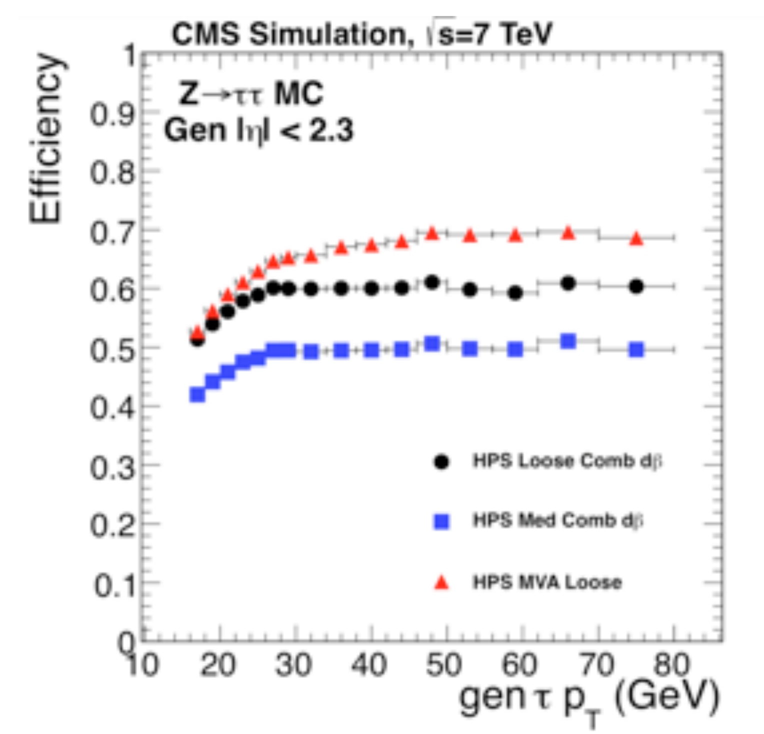
HIG-13-004

- Two analyses: inclusive and VH
  - 1jet and VBF categories
  - Leptons in final state: e, μ, and τ_h
  - Hadronic tau leptons are reconstructed based on the decay modes
    - MVA isolation using relative Σp_T of particles in concentric ΔR rings around τ
    - Discrimination against electrons and muons using EM shower shape, E/p and muon hits



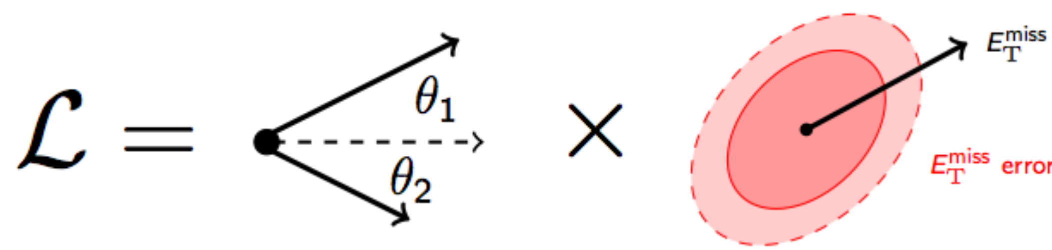




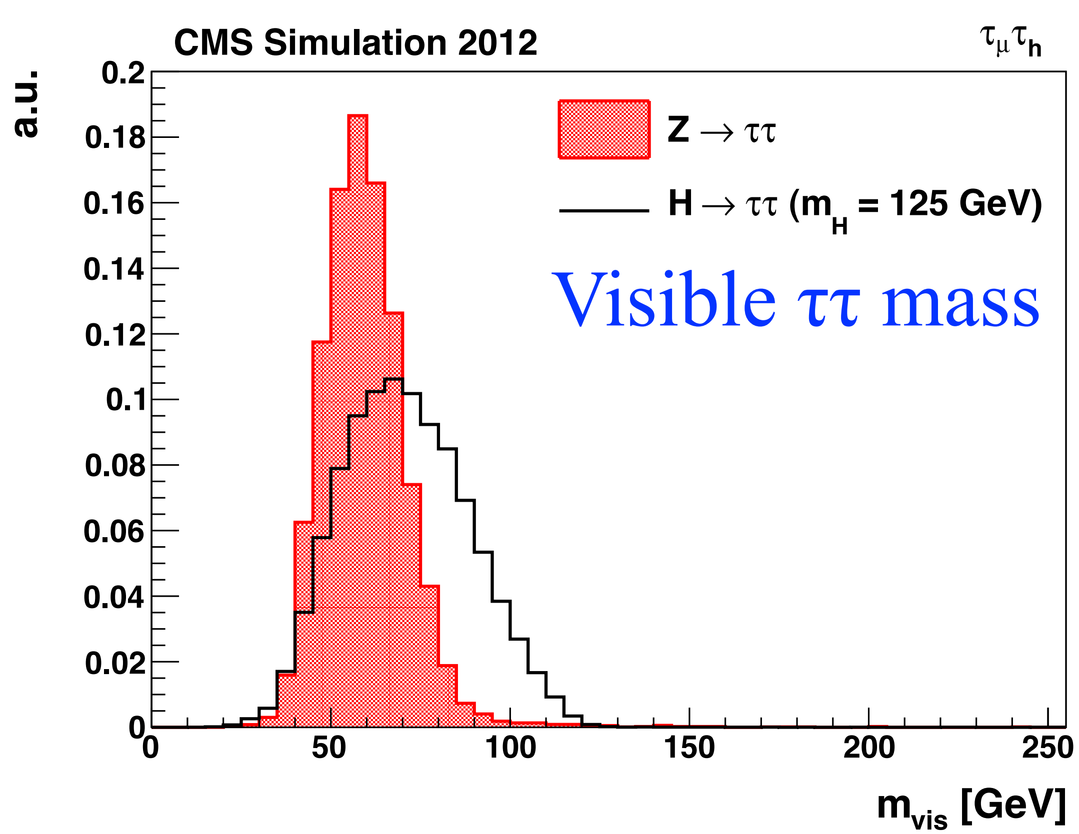


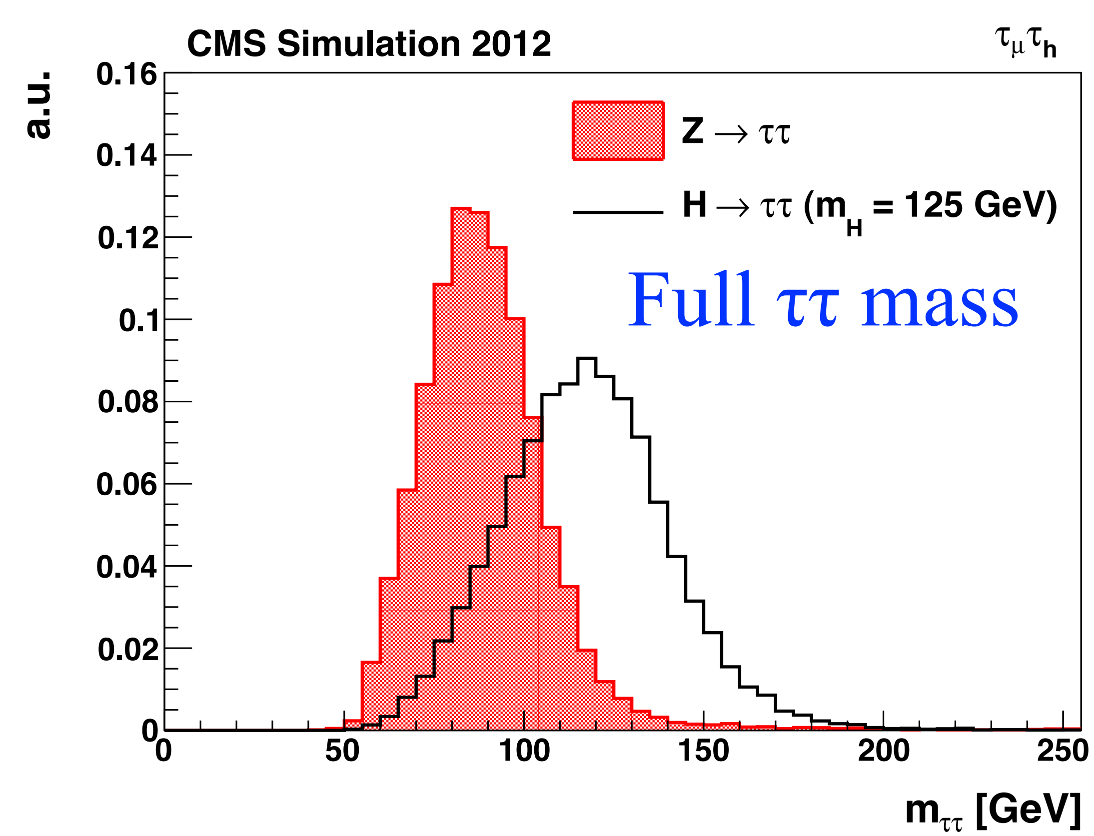
$M_{\tau\tau}$ reconstruction

- Maximum likelihood method used to estimate $M_{\tau\tau}$
  - Event by event basis using 4-vectors of visible decay products, MET, and expected MET resolution



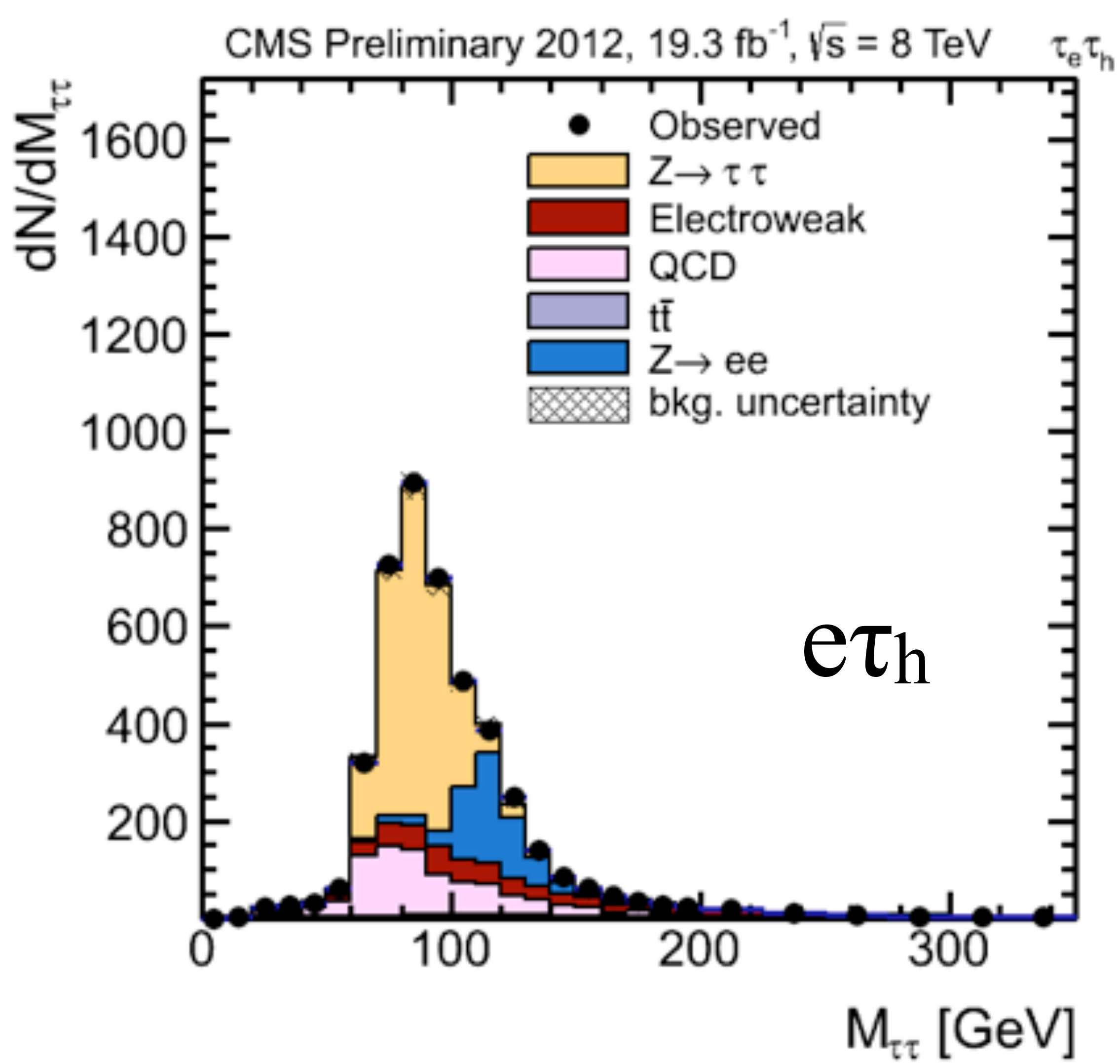
  - Resolution is 15-20% on reconstructed invariant mass of $\tau\tau$ system

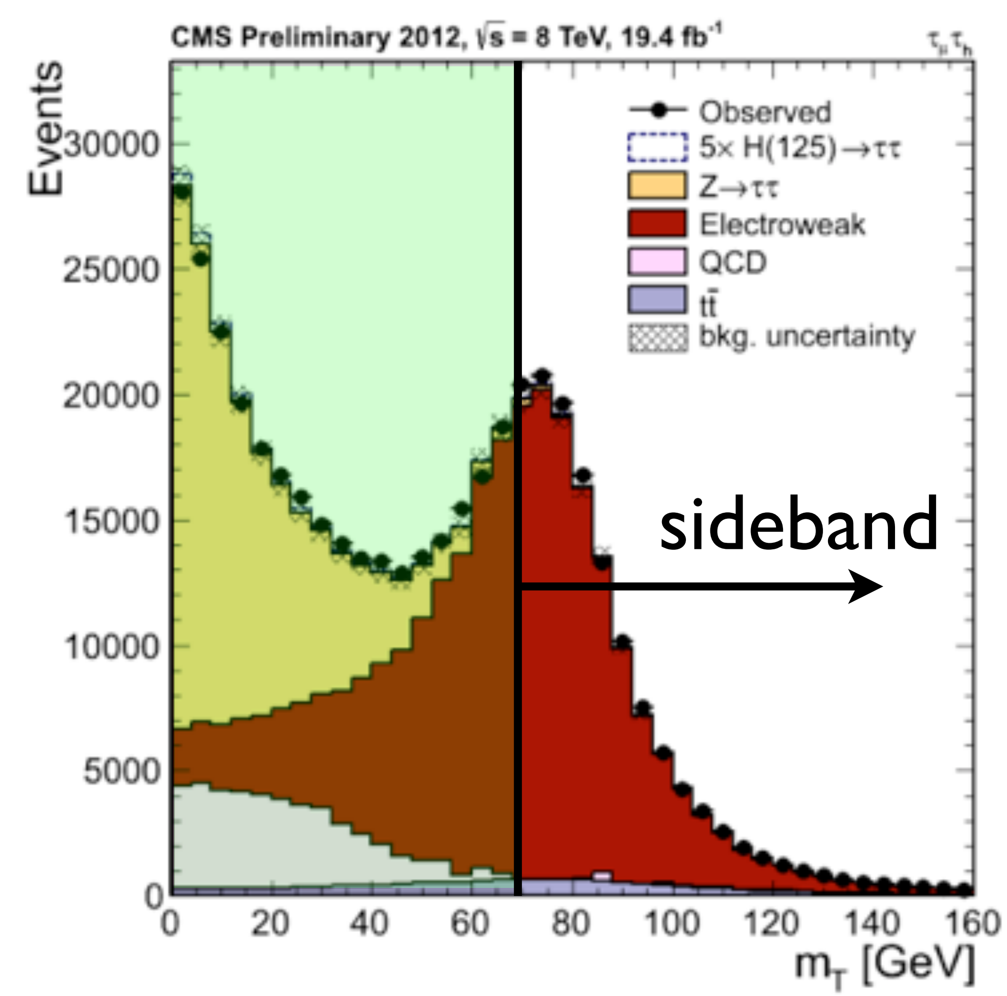




Backgrounds $H \to \tau\tau$

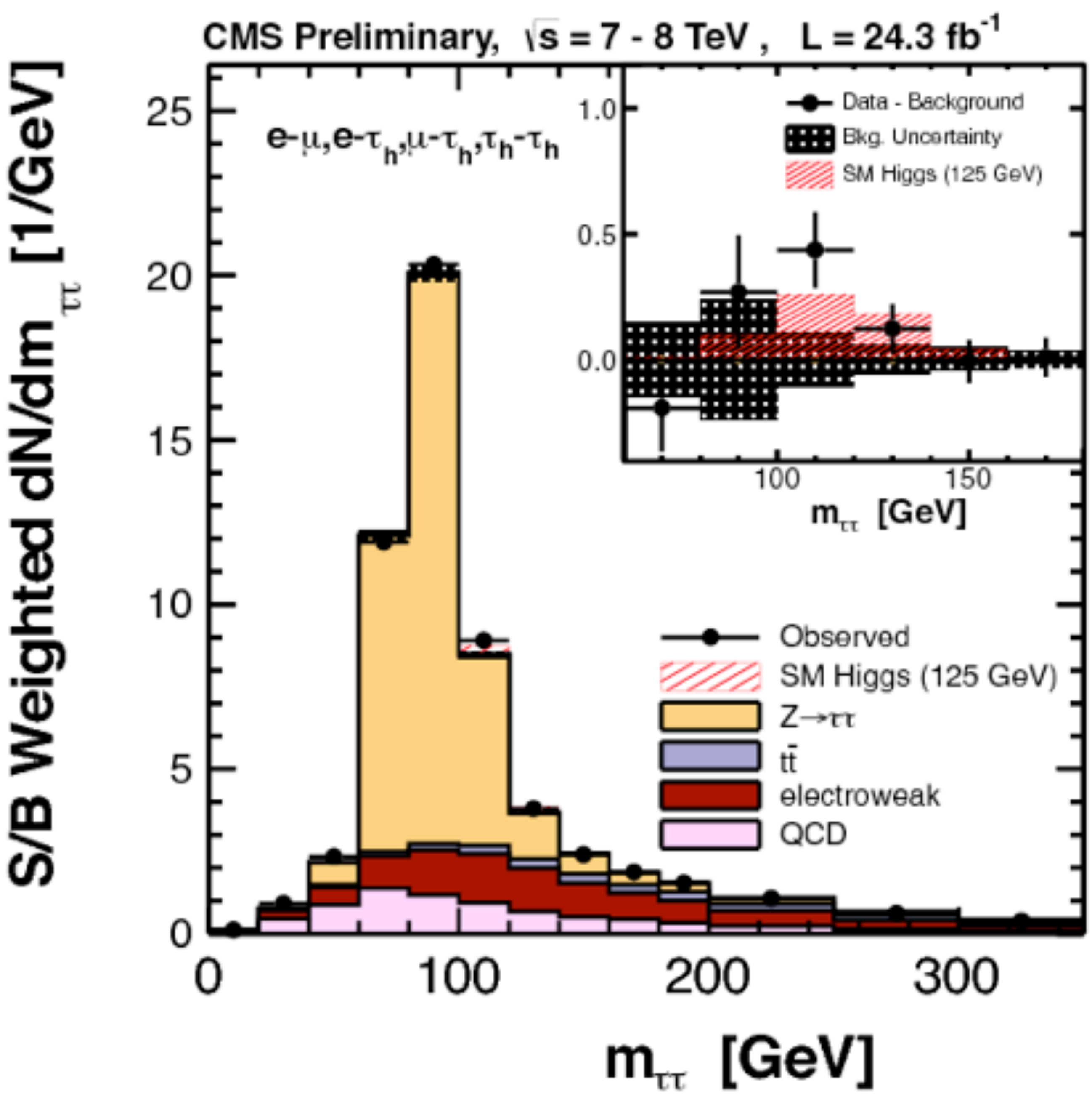
- Several backgrounds, $Z \to \tau\tau$ is the largest
  - $Z \to \tau\tau$: use $Z \to \mu\mu$ data, replace μ with simulated τ decays
  - QCD: use same-sign control sample, corrected for SS/OS ratio
  - $Z \to \ell\ell$: use simulation, correct for $\ell \to \tau_h$ misidentificaiton rate
  - W+jets: simulation shape, normalization from high-M_T sideband



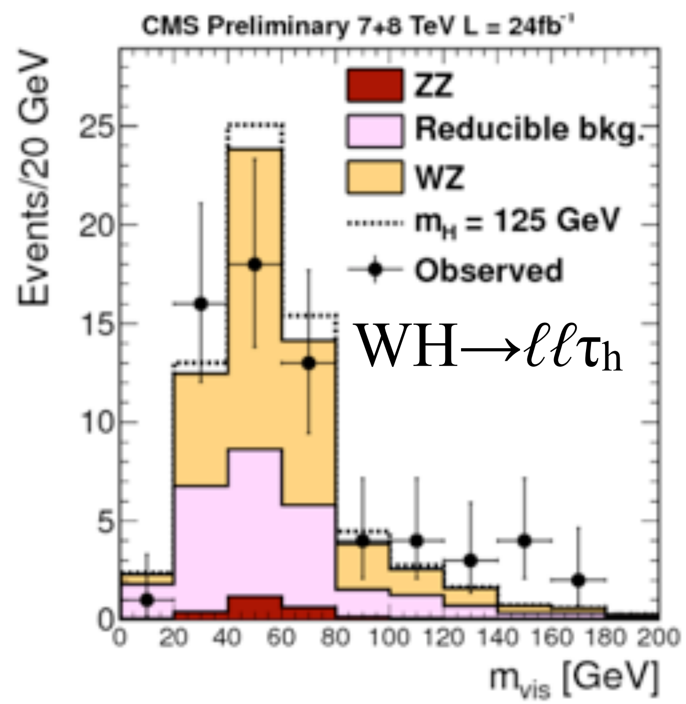


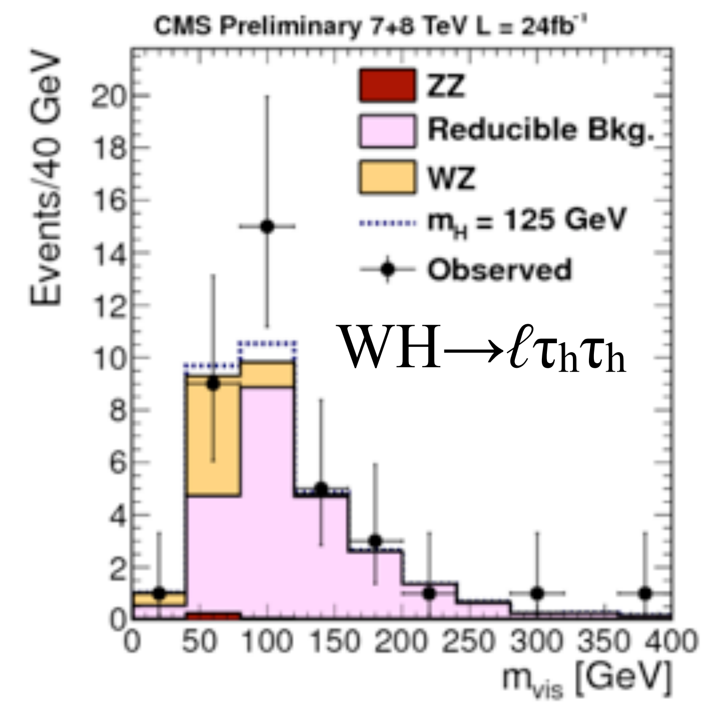
Combining $M_{\tau\tau}$ and VH

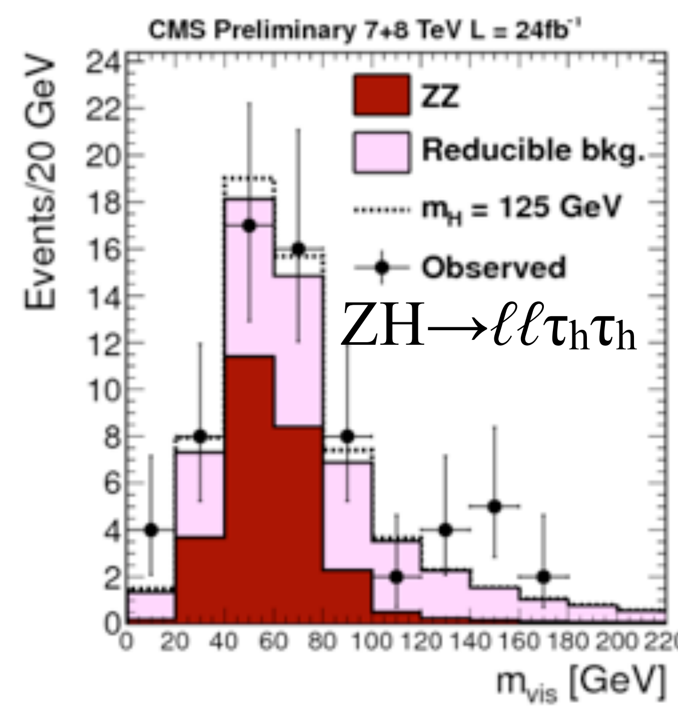
1-jet and VBF categories for eμ, eτh, μτh, and τhτh



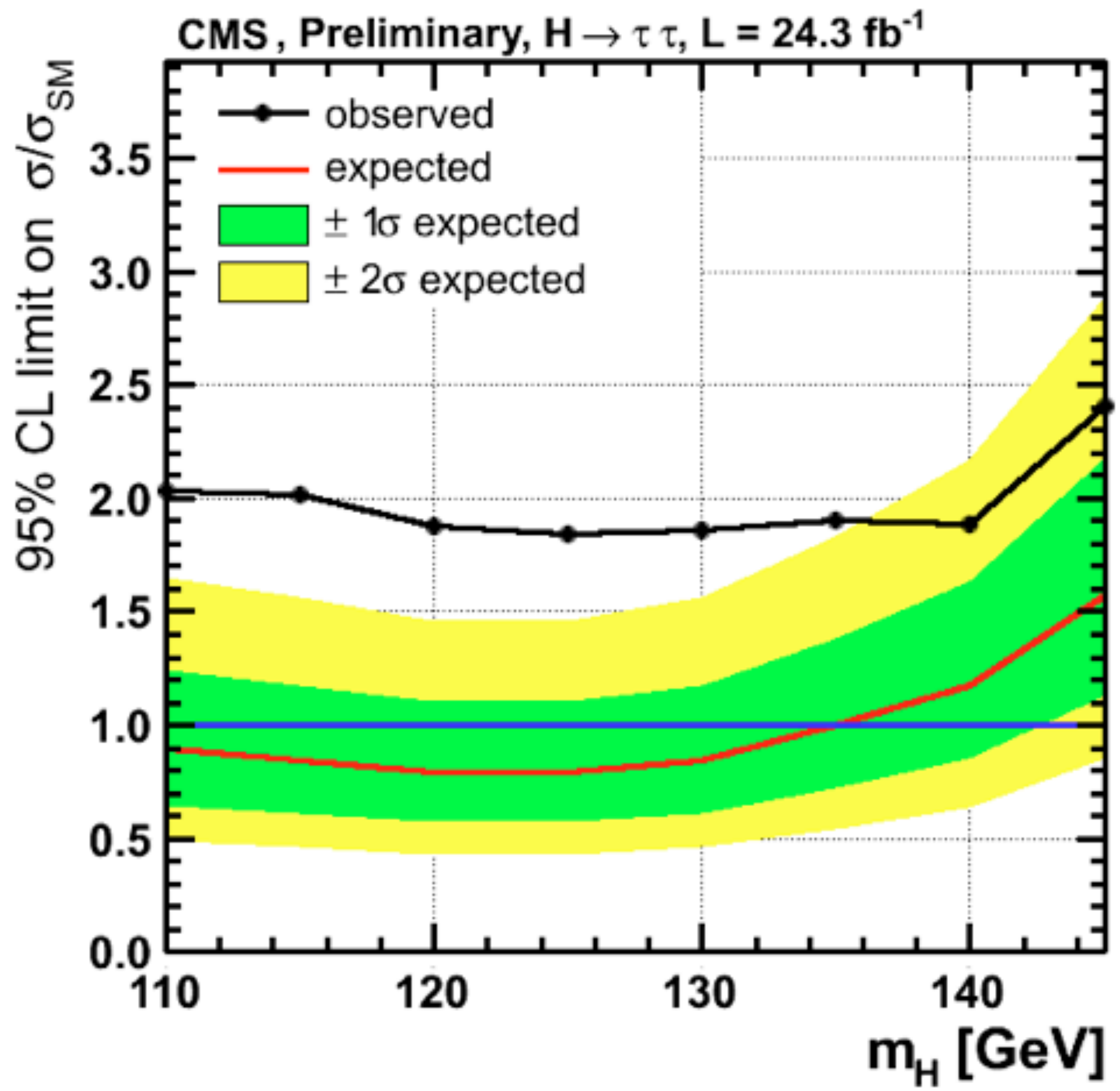
WH and ZH

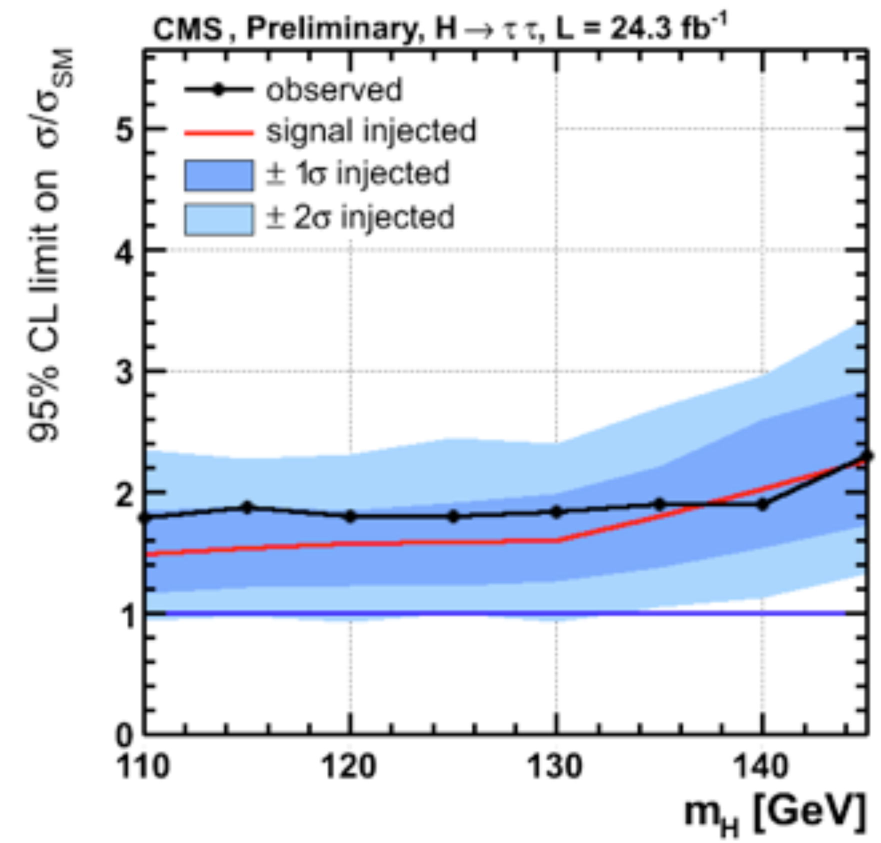


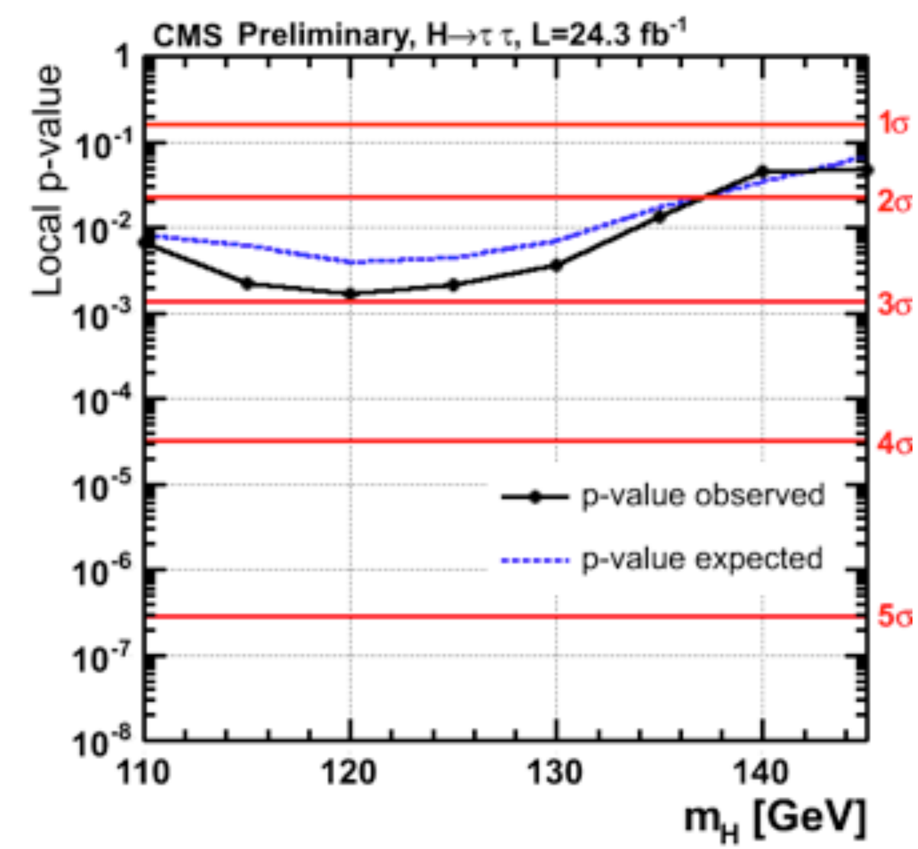




H→ττ results







- Broad excess over the whole m_H range
  - Maximum local significance is at 2.94σ at 120 GeV compatible with 126 GeV Higgs
- Best fit $\sigma/\sigma_{SM} = 1.1 \pm 0.4$

Where does new boson fit best?

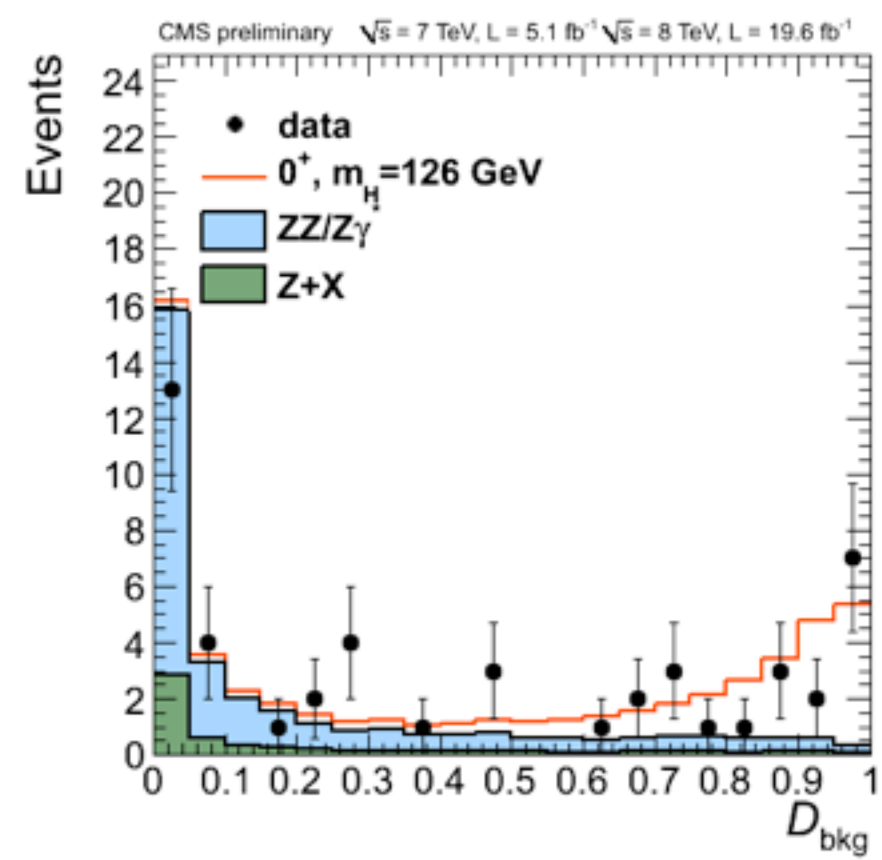
Spin parity studies, H→ZZ

HIG-13-002

- Consider several J^P hypotheses of pure states

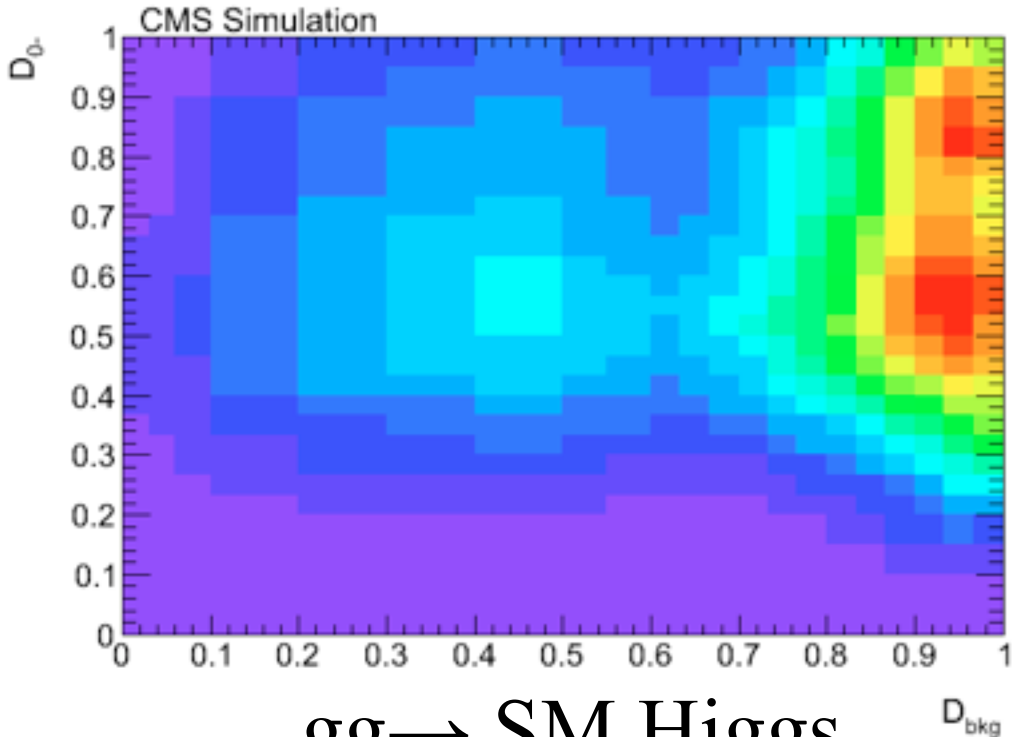
J^P	production	description
0^+	$gg \to X$	SM Higgs boson
0^-	$gg \to X$	pseudoscalar
0^+_h	$gg \to X$	BSM scalar with higher dim operators (decay amplitude)
2^+_{mgg}	$gg \to X$	KK Graviton-like with minimal couplings
$2^+_{mq\bar{q}}$	$q\bar{q} \to X$	KK Graviton-like with minimal couplings
1^-	$q\bar{q} \to X$	exotic vector
1^+	$q\bar{q} \to X$	exotic pseudovector

- Build two kinematic discriminants based on the leading order MEs
  - Discriminator D_{JP} to separate SM Higgs hypothesis from alternative hypothesis
  - Discriminator D_{bkg} to separate SM Higgs from backgrounds
    - Use kinematics and $M_{4\ell}$ information into one discriminant

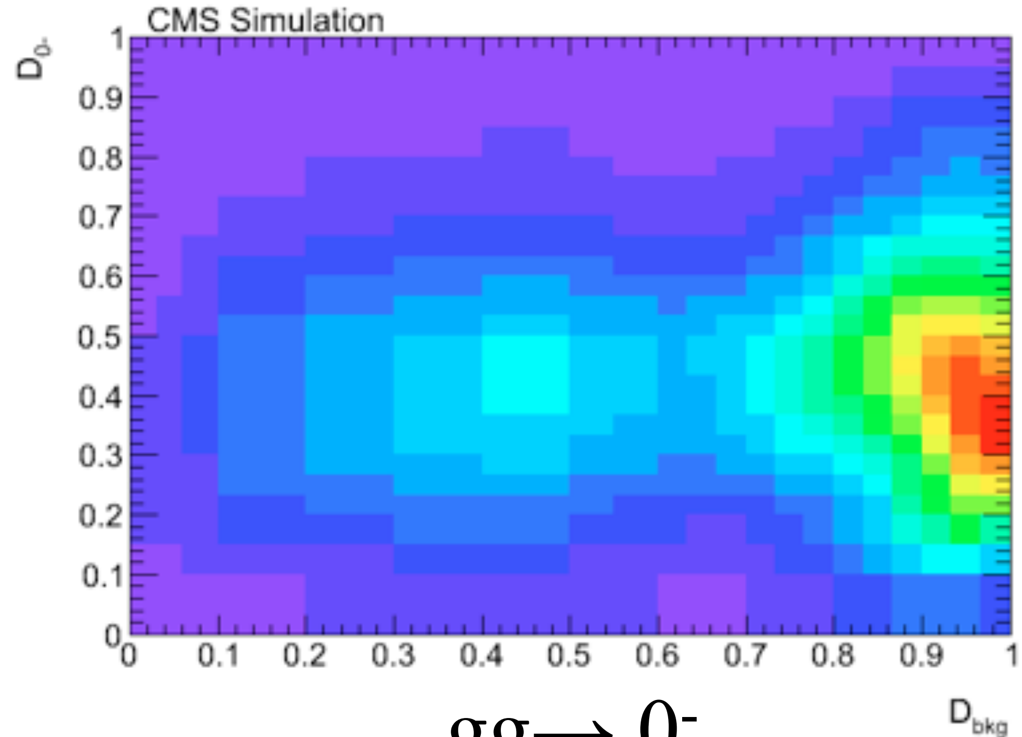


Templates for gg→0^- hypothesis

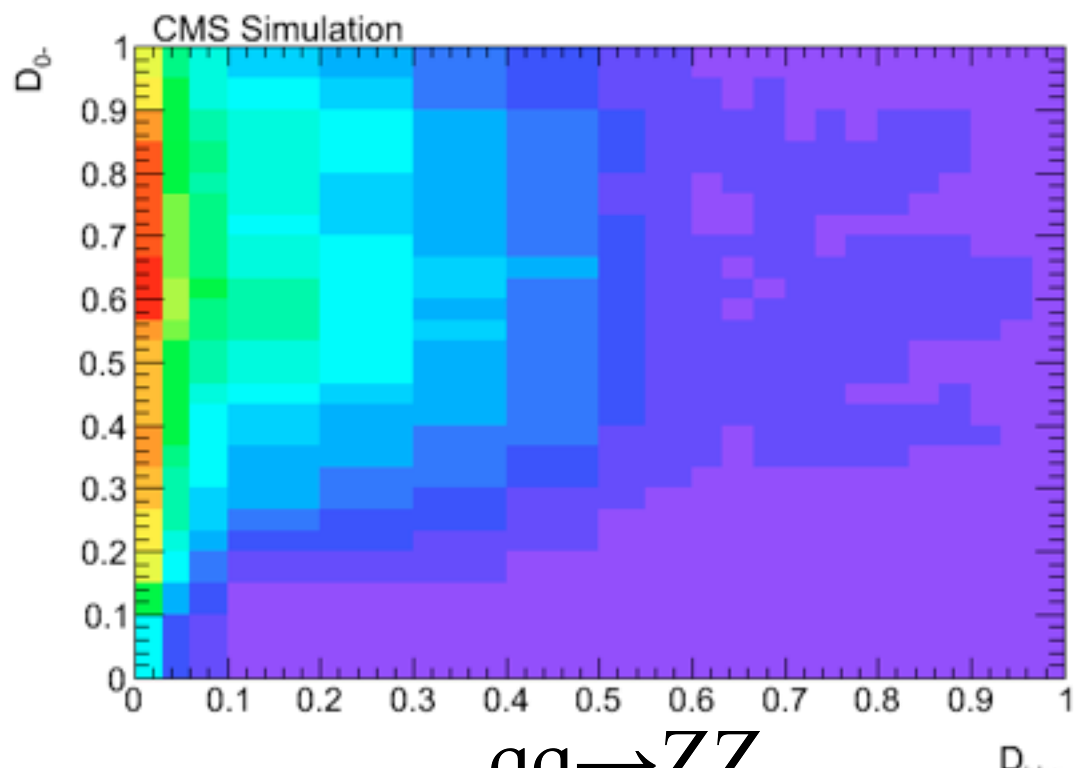
2e2μ final state for 8 TeV



gg→ SM Higgs

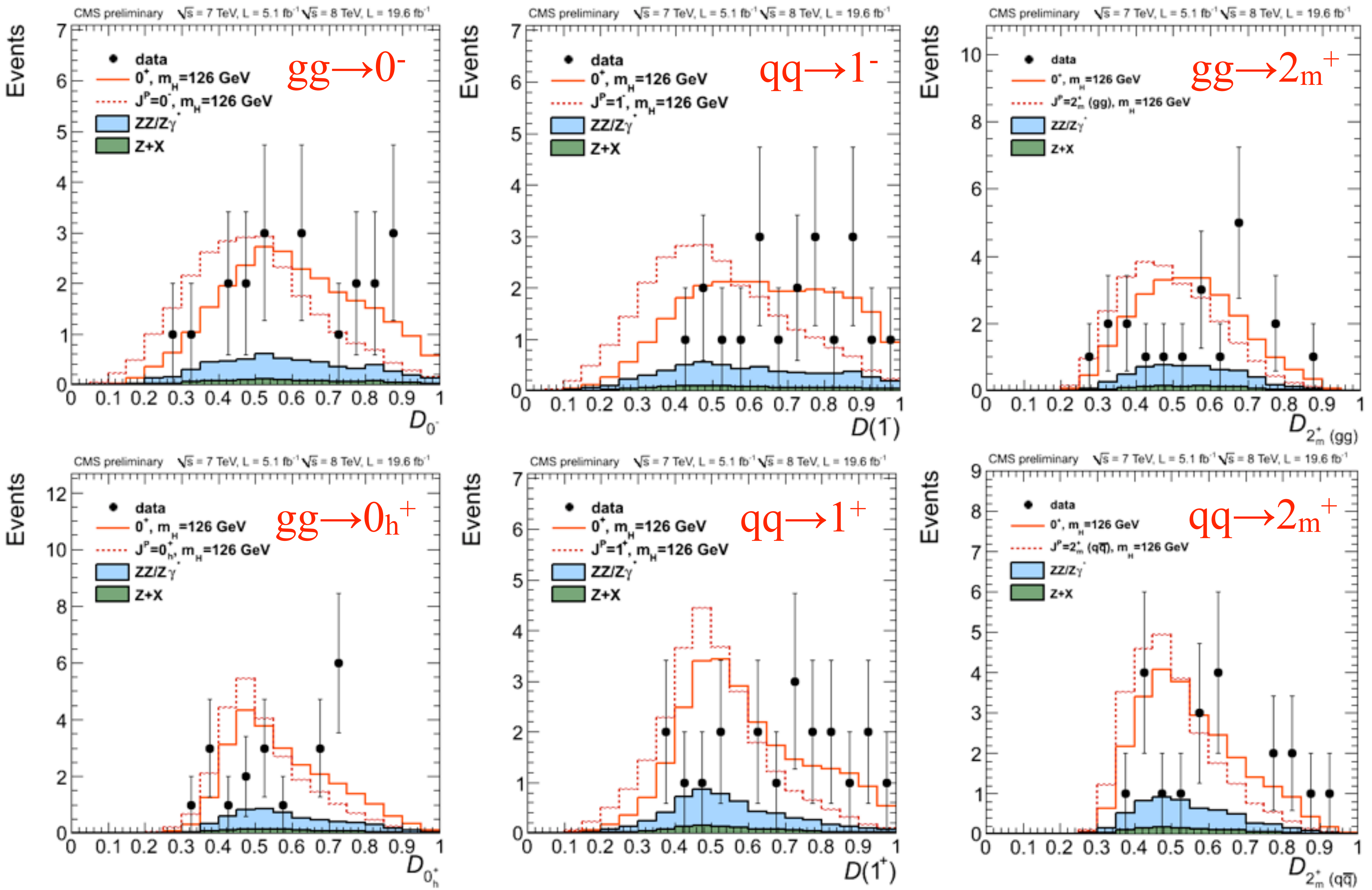


gg→ 0^-

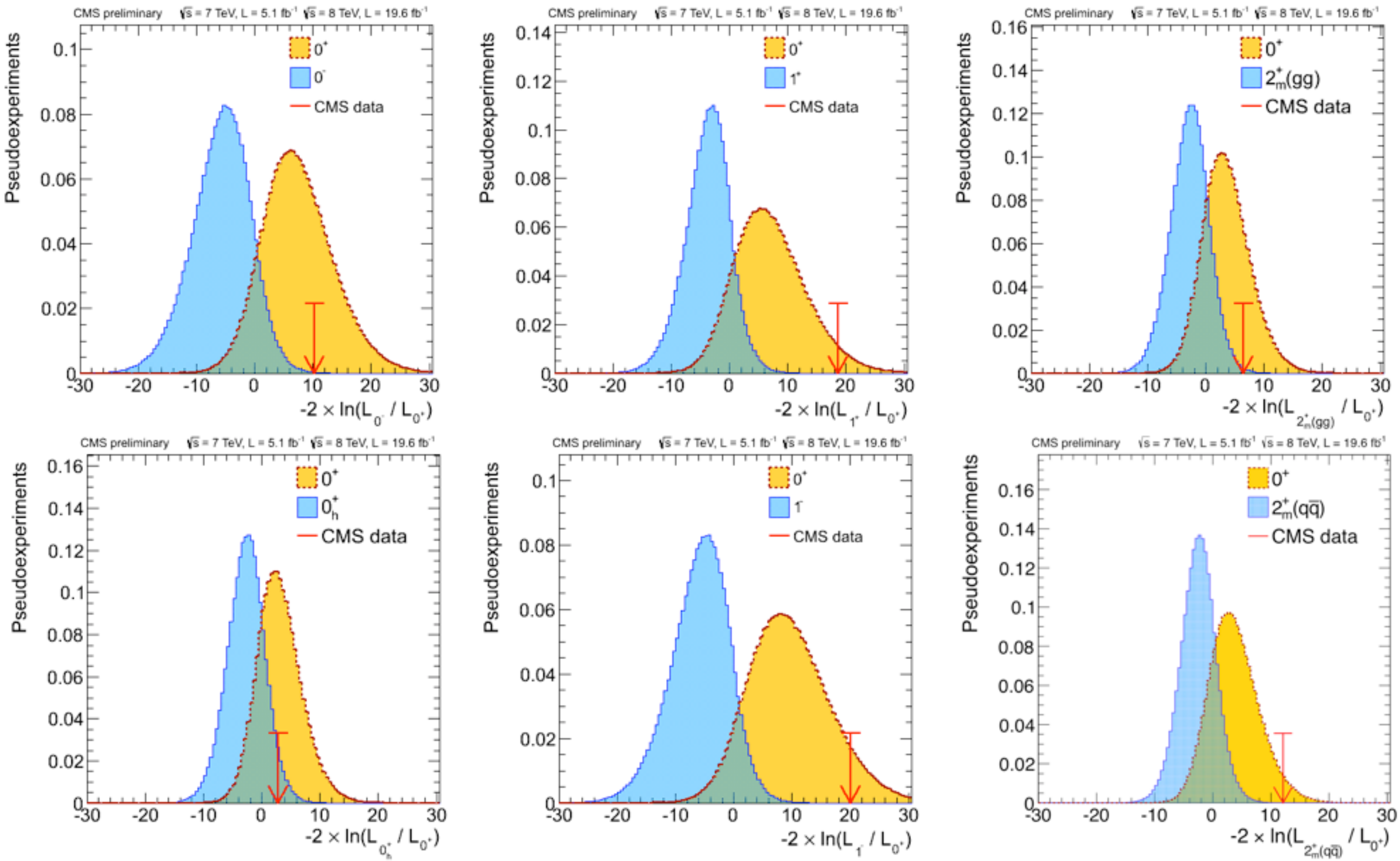


qq→ZZ

D_{JP} distributions ($D_{bkg} > 0.5$)



Spin-parity: test statistics



Spin-parity: $H \rightarrow ZZ$ results

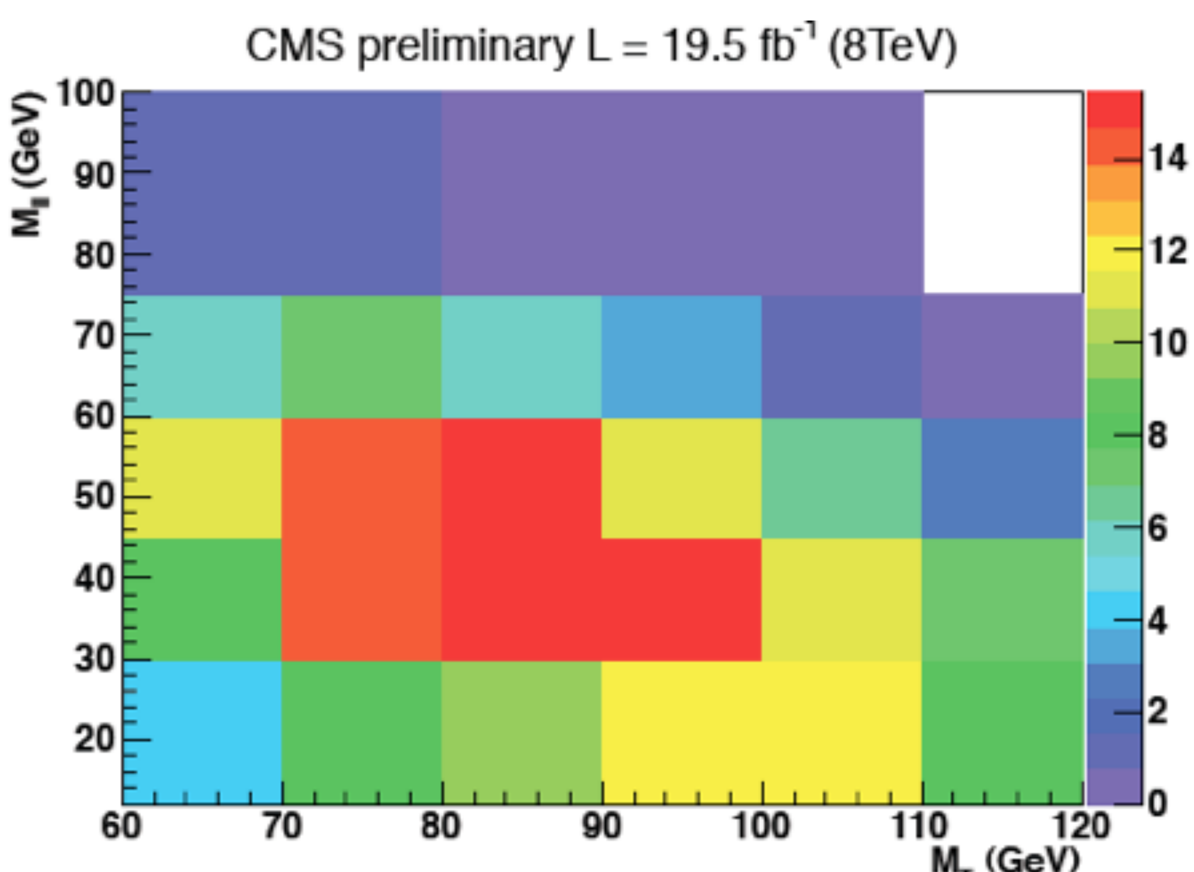
	Expected [σ]		Observed, μ from data [σ]		
	μ=1	μ from data	P(q > Obs | alternative)	P(q > Obs | SM Higgs)	CLs
$gg \rightarrow 0^-$	2.8	2.5	3.3	-0.5	0.16%
$gg \rightarrow 0_h^-$	1.8	1.7	1.7	0.0	8.12%
$qq \rightarrow 1^+$	2.6	2.3	> 4.0	-1.7	<0.01%
$qq \rightarrow 1^-$	3.1	2.8	> 4.0	-1.4	<0.01%
$gg \rightarrow 2_m^+$	1.9	1.8	2.7	-0.8	1.46%
$qq \rightarrow 2_m^+$	1.9	1.7	4.0	-1.8	0.09%

- Pseudo-scalar, spin-1, and spin-2 hypotheses are excluded at 95% C.L. or higher
  - Data is consistent with SM Higgs scenario

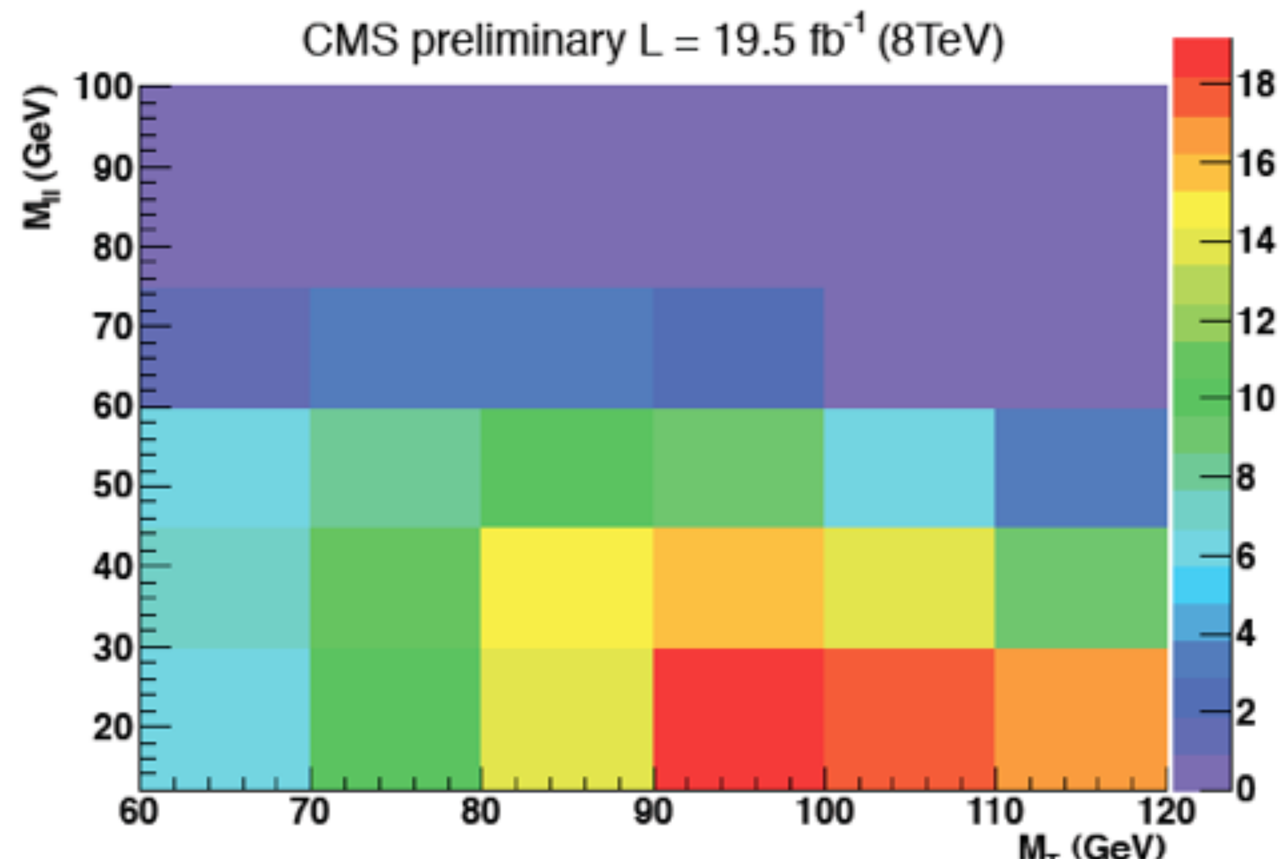
Spin in WW→2ℓ2ν

HIG-13-003

- Use DF 0/1 jet channels to probe spin scenarios
  - Shape-based analysis
- Use 2D templates of M_T and $M_{\ell\ell}$ for SM Higgs and spin-2 minimal coupling scenario ($gg \rightarrow 2_m^+$)

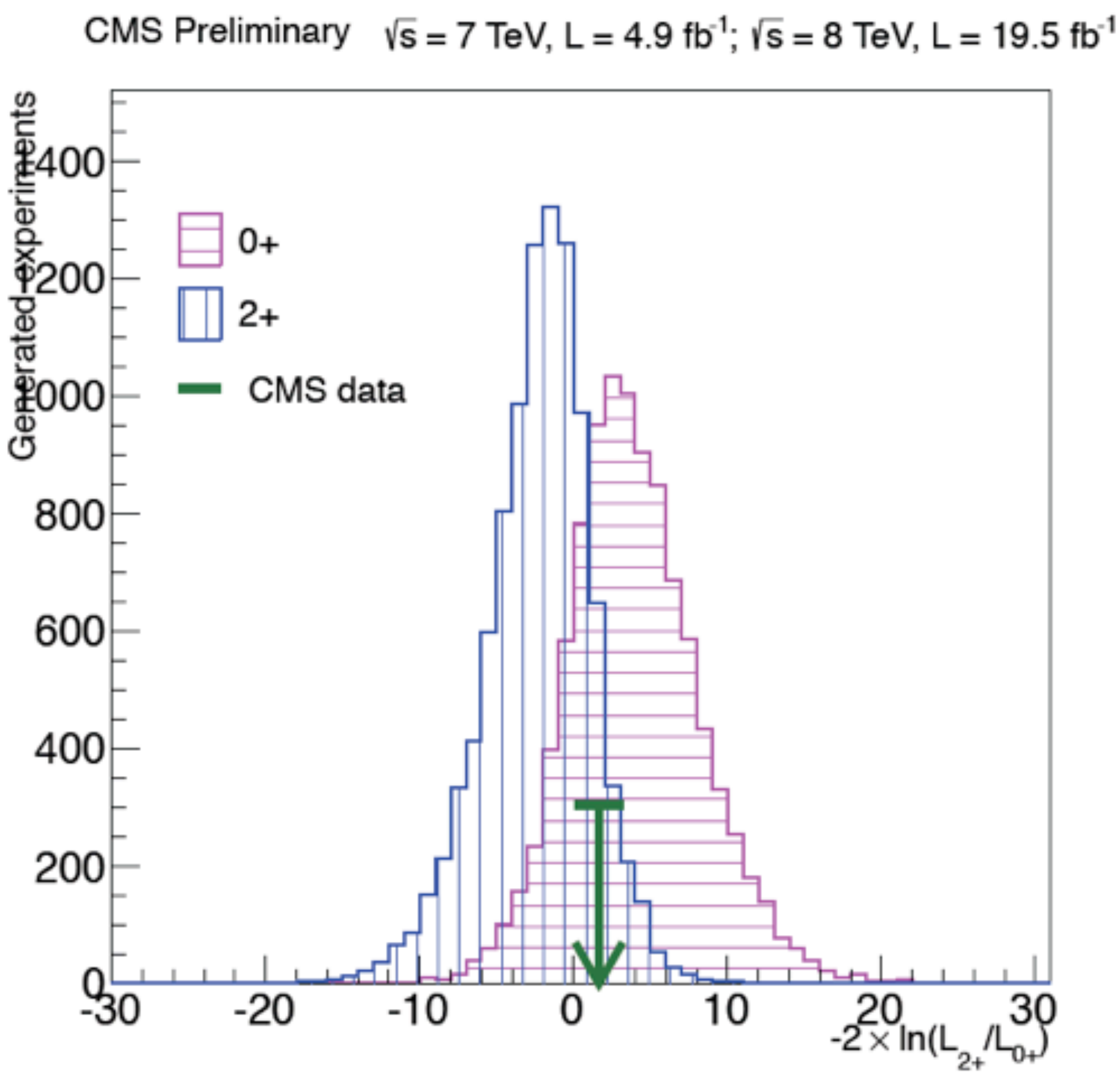


$gg \rightarrow 2_m^+$



gg→SM Higgs

Spin in WW: results

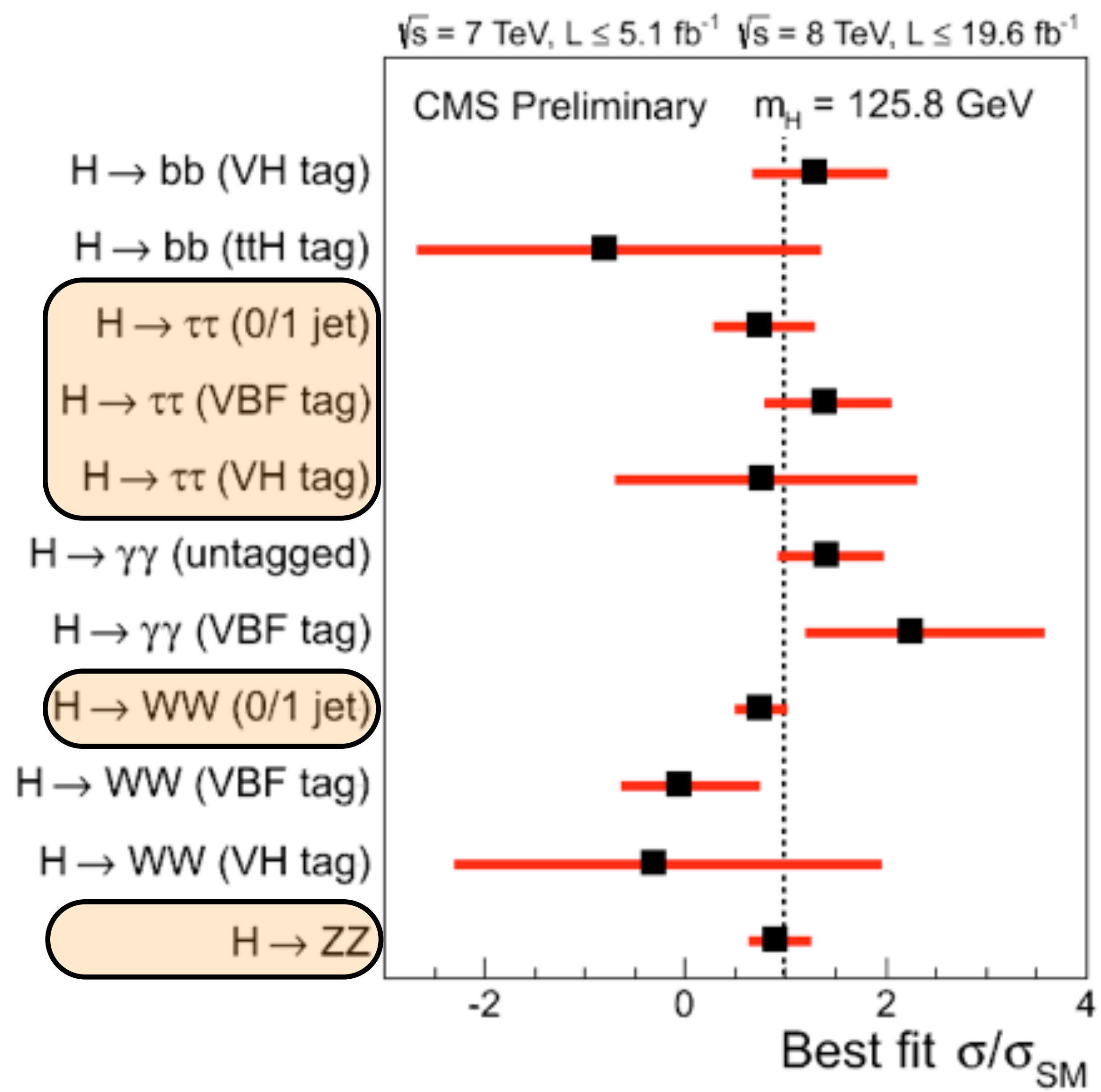


Hypothesis	Expected	Observed
Fix $\mu = 1$		
$gg \to 0^+$	1.9σ	0.9σ
$gg \to 2_m^+$	2.4σ	1.3σ
Fit μ from data		
$gg \to 0^+$	1.5σ	0.5σ
$gg \to 2_m^+$	1.8σ	1.3σ

- Expected separation is at the 2σ level
  - Data consistent with either hypothesis

Summary of Higgs results

- So far it looks as if the newly discovered particle is the SM Higgs boson
  - Data are consistent with SM 0^+ scenario and disfavor pure pseudo-scalar, vector, pseudo-vector, and spin-2 resonances with minimal couplings
  - Signal strengths are also consistent with SM prediction



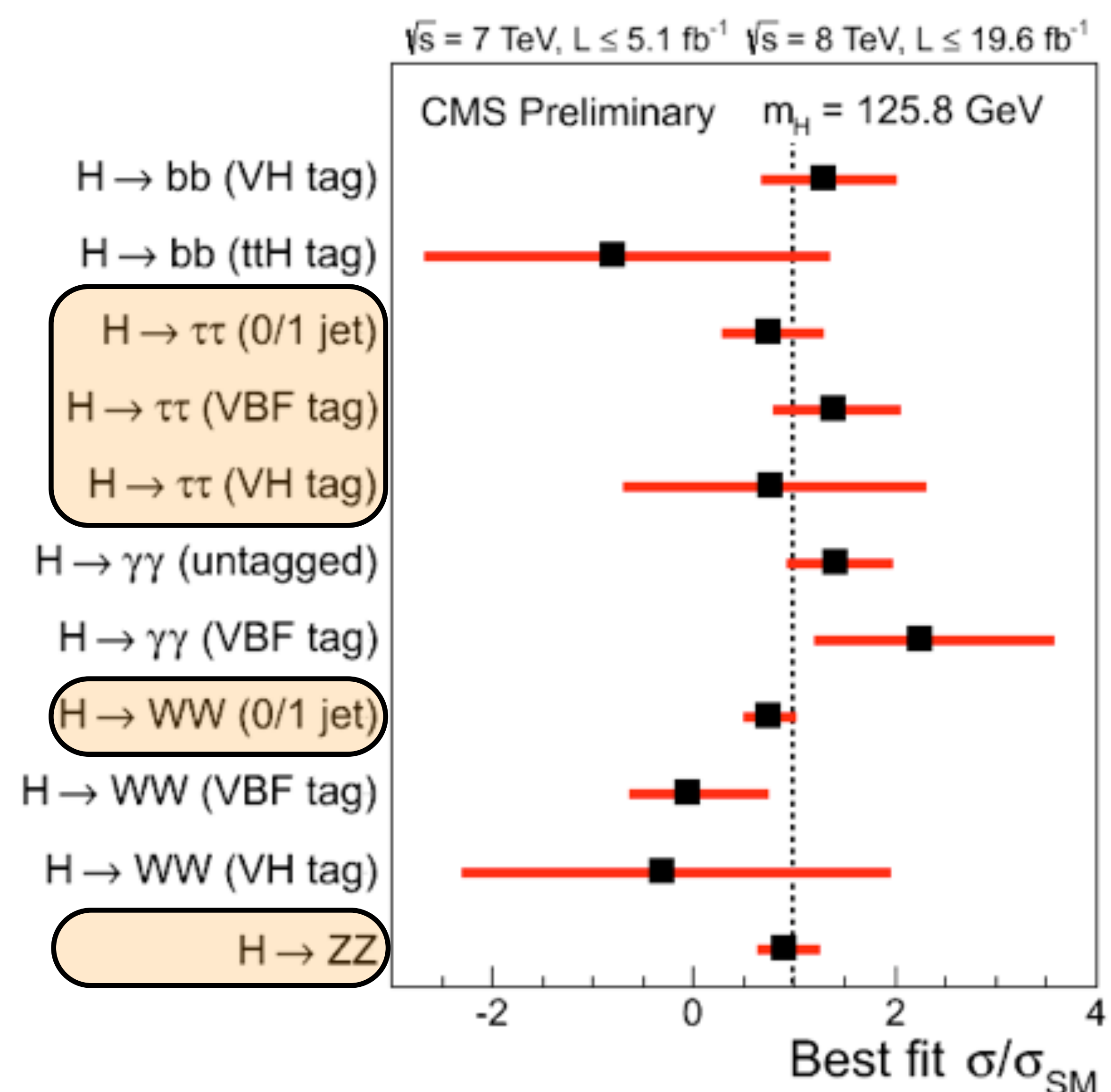
- Mass is ~125.8 GeV
  - HCP combination of γγ and inclusive ZZ yields

$$M_X = 125.8 \pm 0.6 \text{ GeV}$$

    - Dead on with the updated mass ZZ measurement

Summary of Higgs results

- So far it looks as if the newly discovered particle is the SM Higgs boson
  - Data are consistent with SM 0^+ scenario and disfavor pure pseudo-scalar, vector, pseudo-vector, and spin-2 resonances with minimal couplings
  - Signal strengths are also consistent with SM prediction



- Mass is ~125.8 GeV
  - HCP combination of γγ and inclusive ZZ yields

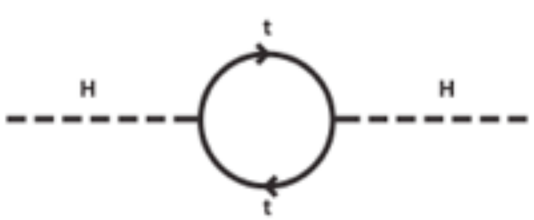
$$M_X = 125.8 \pm 0.6 \text{ GeV}$$

  - Dead on with the updated mass ZZ measurement

How does it affect the rest of the CMS physics program?

Questions, questions…

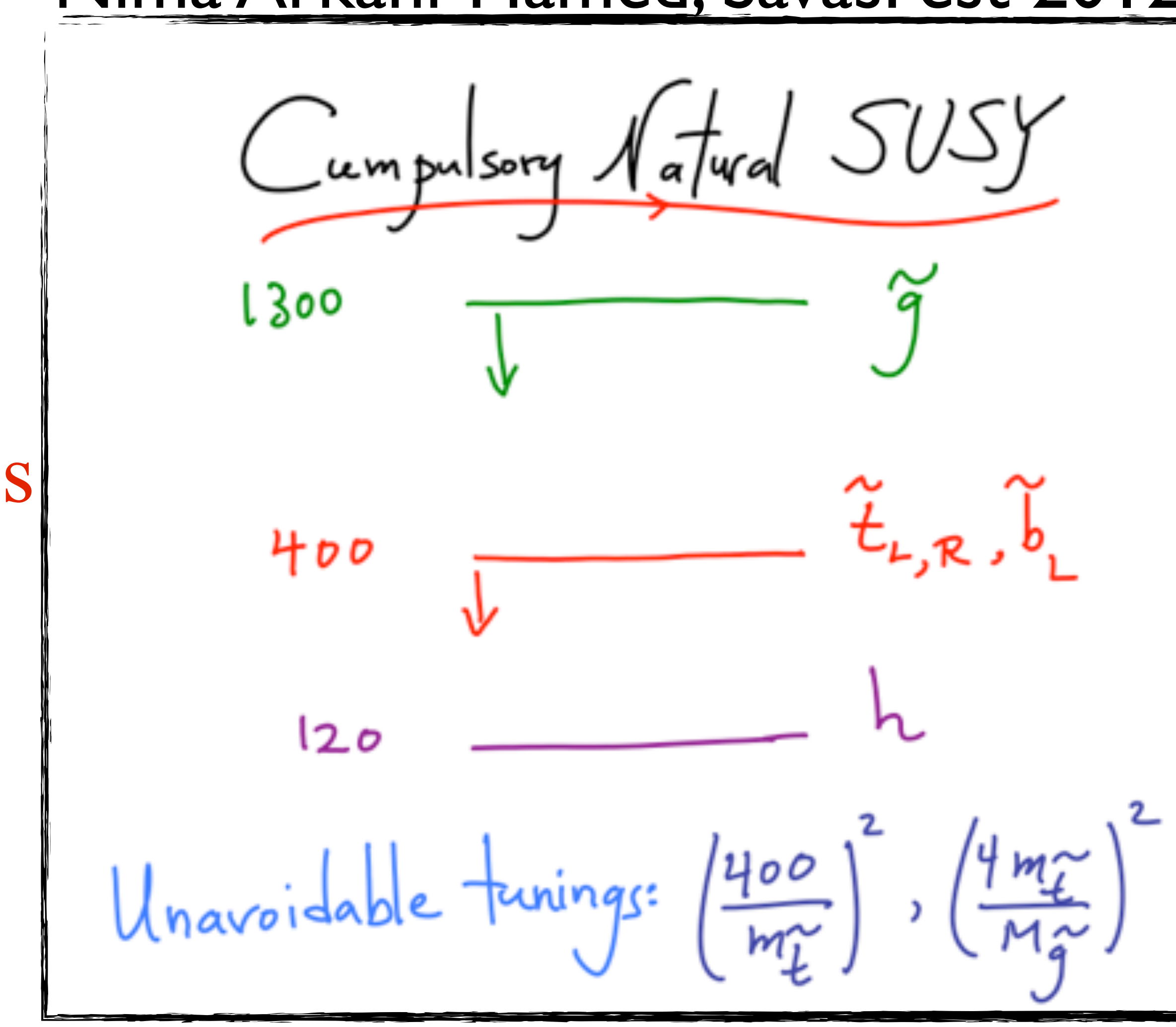
- What, if anything, makes the Higgs mass light?
  - QFT: $m_H^2 = m_H^{2\ tree} + \Delta m_H^{2\ top} + \Delta m_H^{2\ W,Z} + \Delta m_H^{2\ self} \sim \mathcal{O}(125)\mathrm{GeV}$
  - Corrections diverge quadratically $\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}[\Lambda_{\mathrm{UV}}^2 + \ldots]$
- Either we live in a fine-tuned Universe or QFT is wrong, or there must be some new physics to take care of divergences
  - SUSY: offers DM candidate, unification of couplings, and solves Higgs mass divergency



$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}[\Lambda_{\mathrm{UV}}^2 + \ldots]$

$\Delta m_H^2 = \frac{\lambda_s}{8\pi^2}[\Lambda_{\mathrm{UV}}^2 + \ldots]$

Nima Arkani-Hamed, SavasFest 2012



Natural *vs.* Unnatural

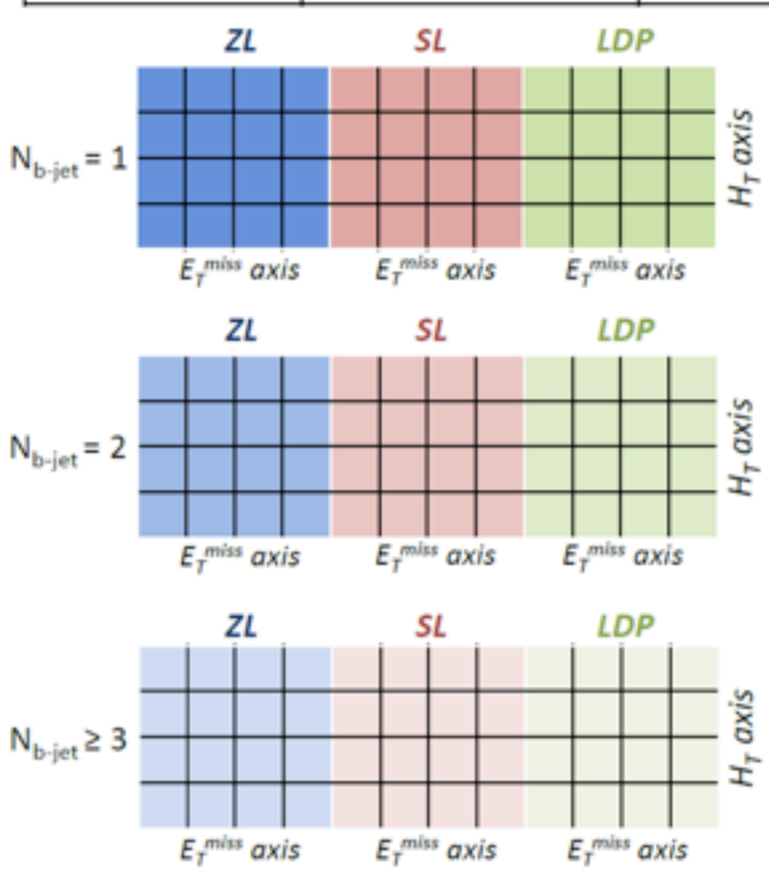
Natural	Unnatural
SUSY - Light sbottoms, stops	Split SUSY - Long-lived particles
Extra dimensions - High mass KK partners (X$\rightarrow$ VV, $\ell\ell$, $\gamma\gamma$, top pairs)	Something else? - New physics that gives us DM candidate - …
Compositeness - Vector-like partner to top quark, new strong-like interaction	No new physics at currently reachable energies - Limits, limits, limits…

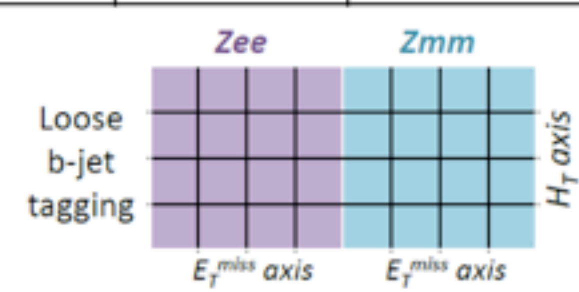
Searching for SUSY

SUS-12-024

- Light stops, sbottoms: final states include multiple jets, leptons, and MET
- (b)jets + MET
  - Use 176 mutually exclusive categories

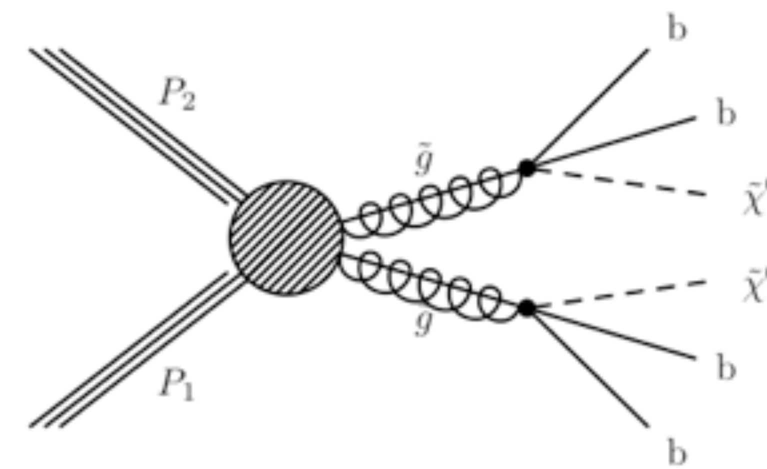
Event sample legend				
ZL = Zero Lepton; signal sample	*SL* = Single Lepton; top & W+jets control sample	*LDP* = low $\Delta\hat{\phi}_{min}$; QCD control sample	*Zee* = $Z \to e^+e^-$; Z to $\nu\bar{\nu}$ control sample	*Zmm* = $Z \to \mu^+\mu^-$; Z to $\nu\bar{\nu}$ control sample

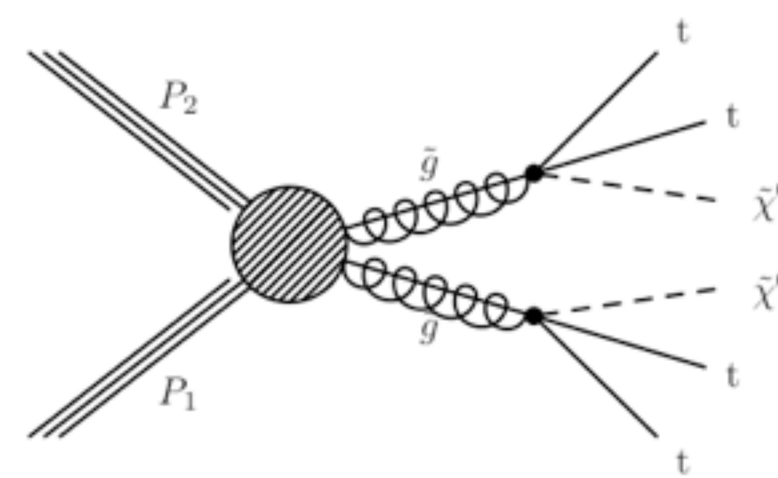


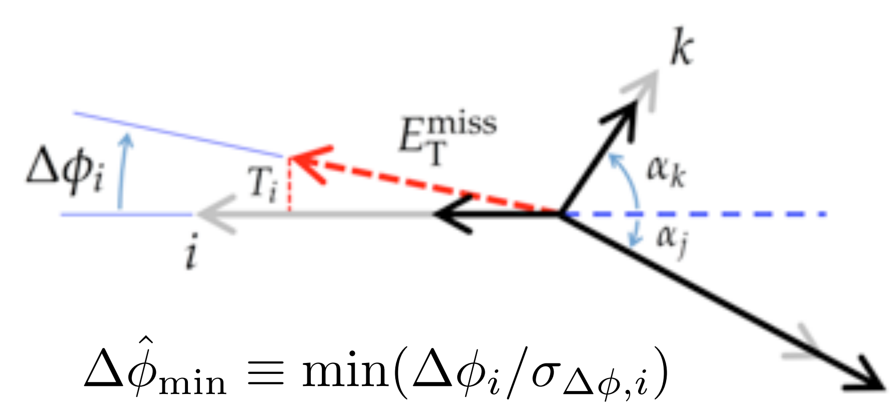


Bin	H_T (GeV)	E_T^{miss} (GeV)
1	400 – 500 (HT1)	125 – 150 (MET1)
2	500 – 800 (HT2)	150 – 250 (MET2)
3	800 – 1000 (HT3)	250 – 350 (MET3)
4	> 1000 (HT4)	> 350 (MET4)

$$\mu^{t\bar{t}+\mathrm{Wjets}}_{\mathrm{ZL};bin} = S^{t\bar{t}+\mathrm{Wjets}}_{bin} \cdot R^{t\bar{t}+\mathrm{Wjets}}_{\mathrm{ZL/SL}} \cdot \mu^{t\bar{t}+\mathrm{Wjets}}_{\mathrm{SL};bin}$$



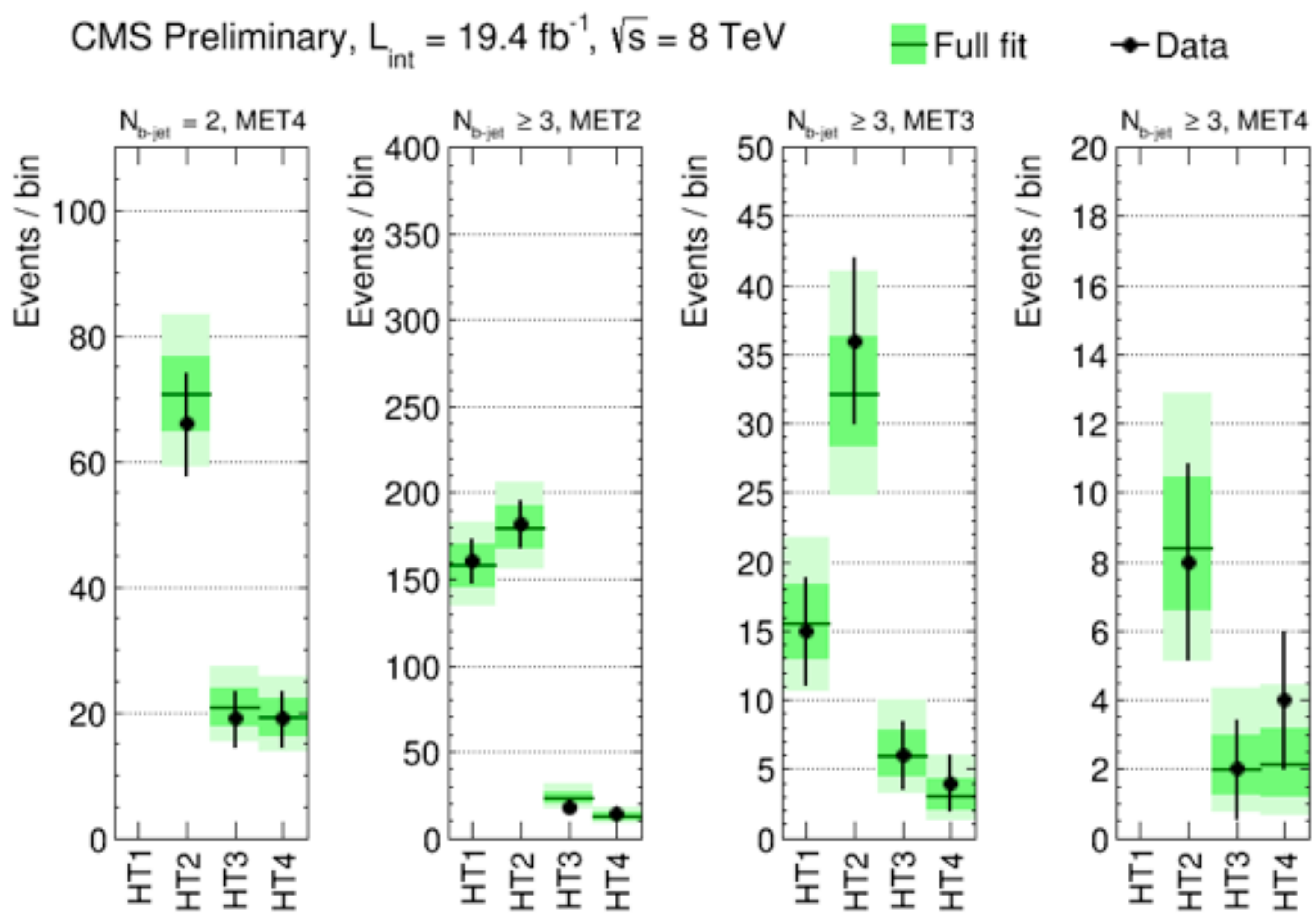




$$\Delta\hat{\phi}_{\mathrm{min}} \equiv \min(\Delta\phi_i/\sigma_{\Delta\phi,i})$$
$$\sigma_{\Delta\phi,i} = \arcsin(\sigma_{T_i}/\mathrm{MET})$$

Searching for SUSY (jets+MET)

- Use global fit to extract contributions from different backgrounds and compare predictions to data in bins most sensitive to signal

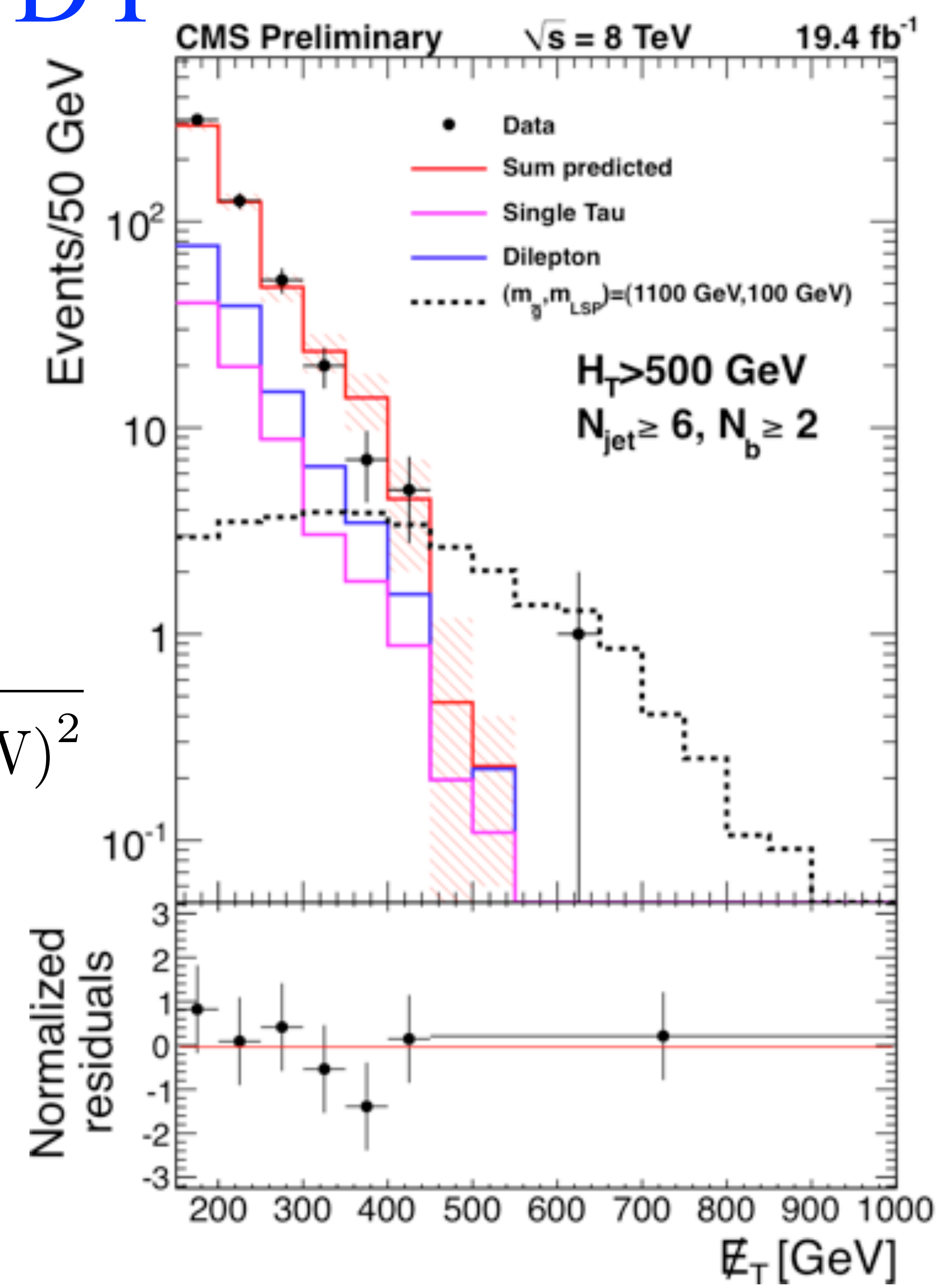


  - No evidence for signal…

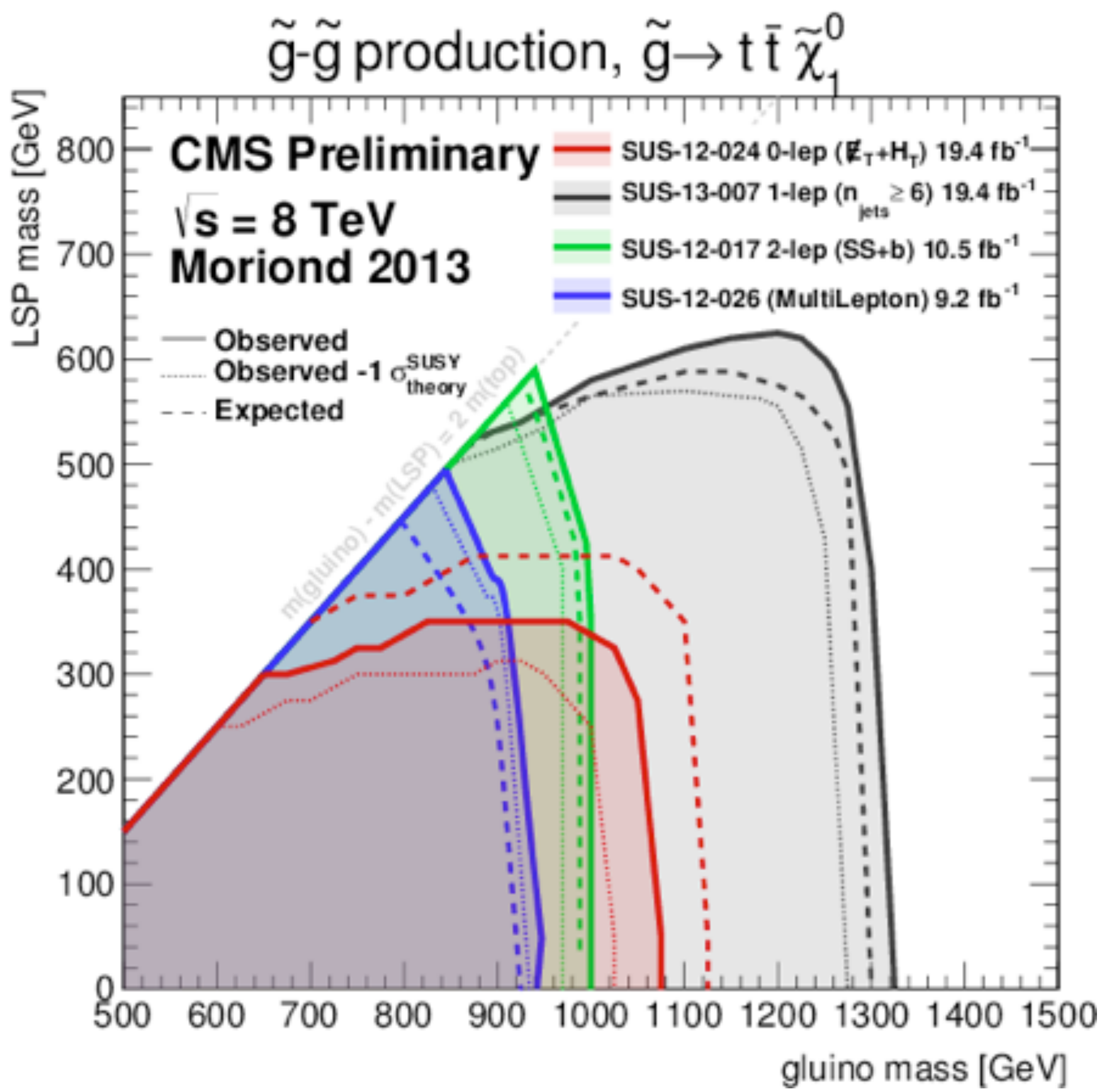
Searching for SUSY: ℓ+jets+MET

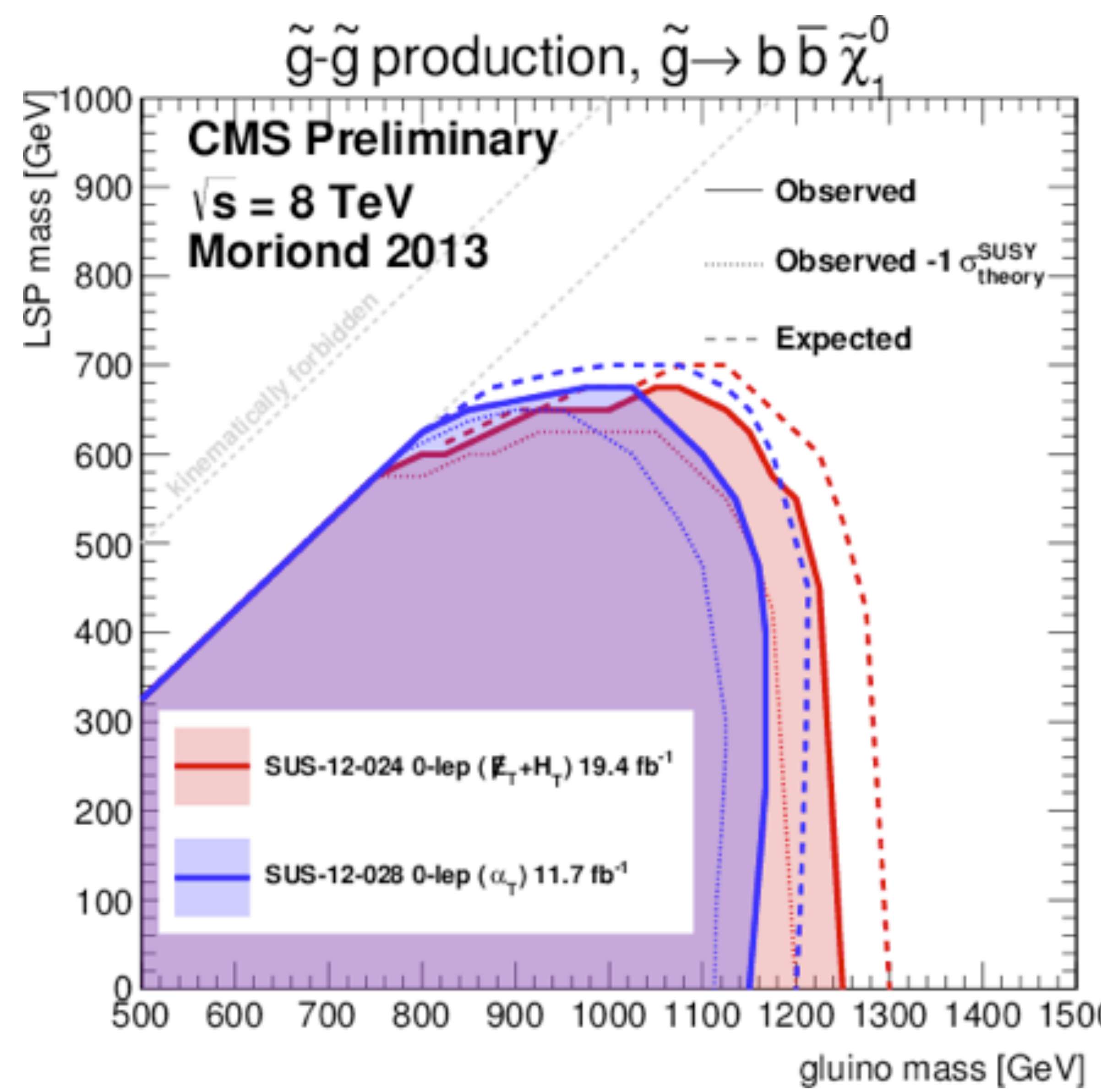
SUS-13-007

- **Major backgrounds: tt+jets and DY**
  - Lepton Spectrum estimation method:
    - Use lepton p_T in signal to predict MET from tt+jets
    - Use control sample ($\ell\ell$+jets) to infer DY contribution
  - $\Delta\varphi$ method:
    - Use $\Delta\varphi(W, \ell)$ and $S_T^{\mathrm{lep}} \equiv \sqrt{p_T(W)^2 + M_T(W)^2}$
    - For top events $\Delta\varphi(W, \ell)$ is small, while DY contribution has flat $\Delta\varphi(W, \ell)$. Use low b-tagged jet samples to calibrate this background



Summary plots on SUSY

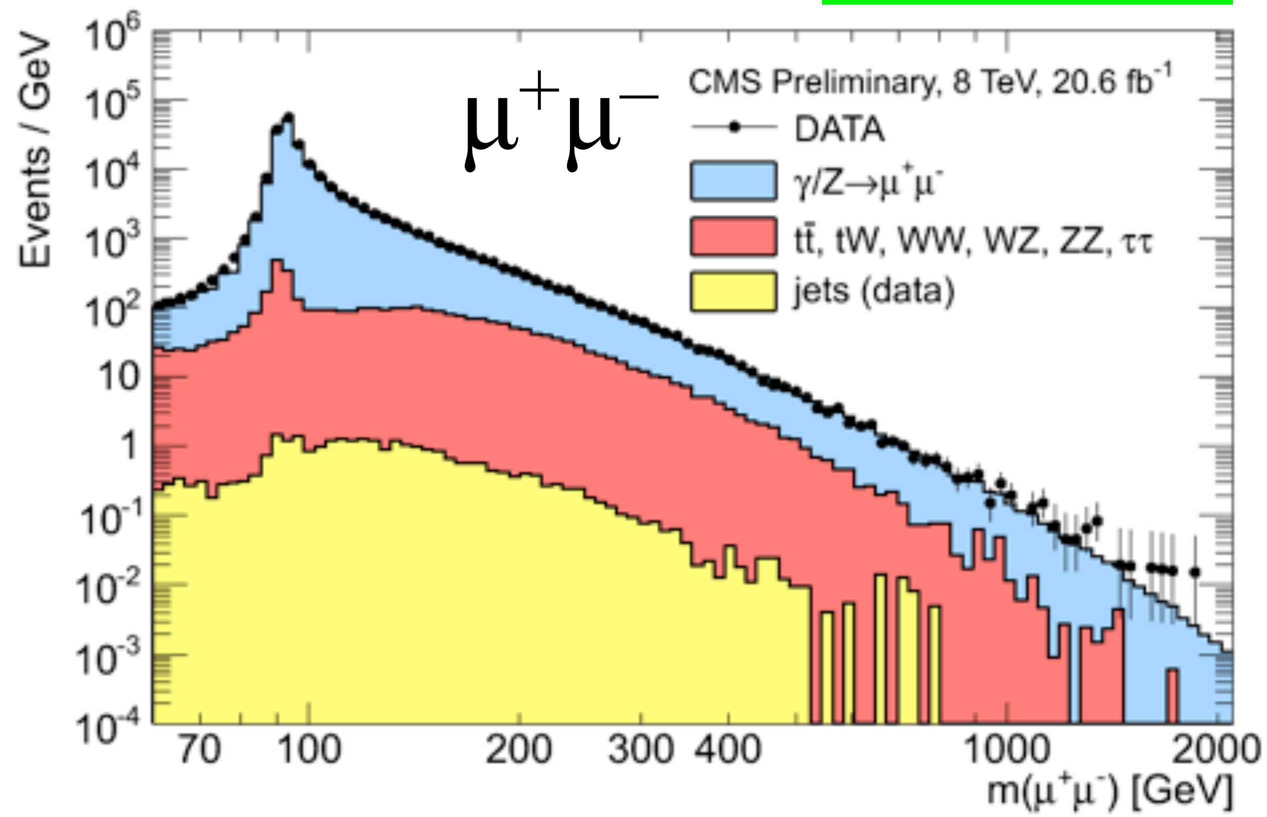


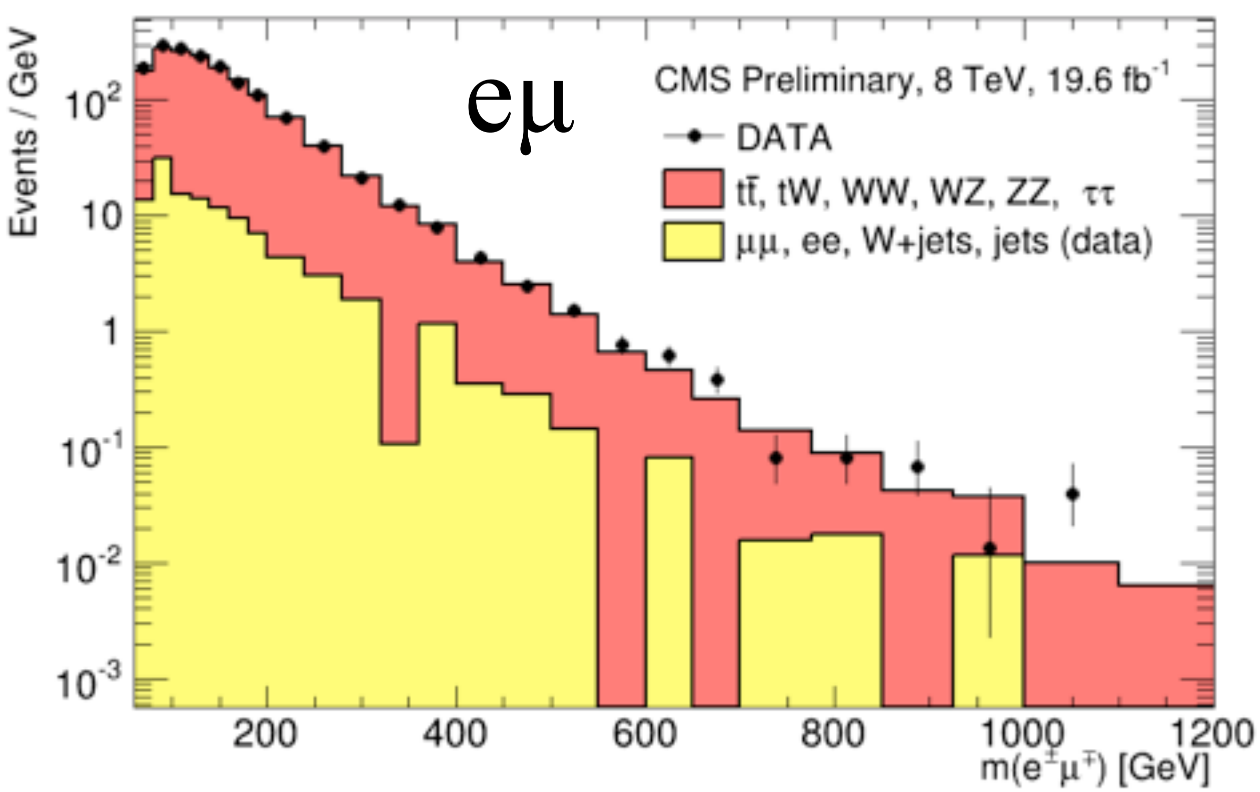


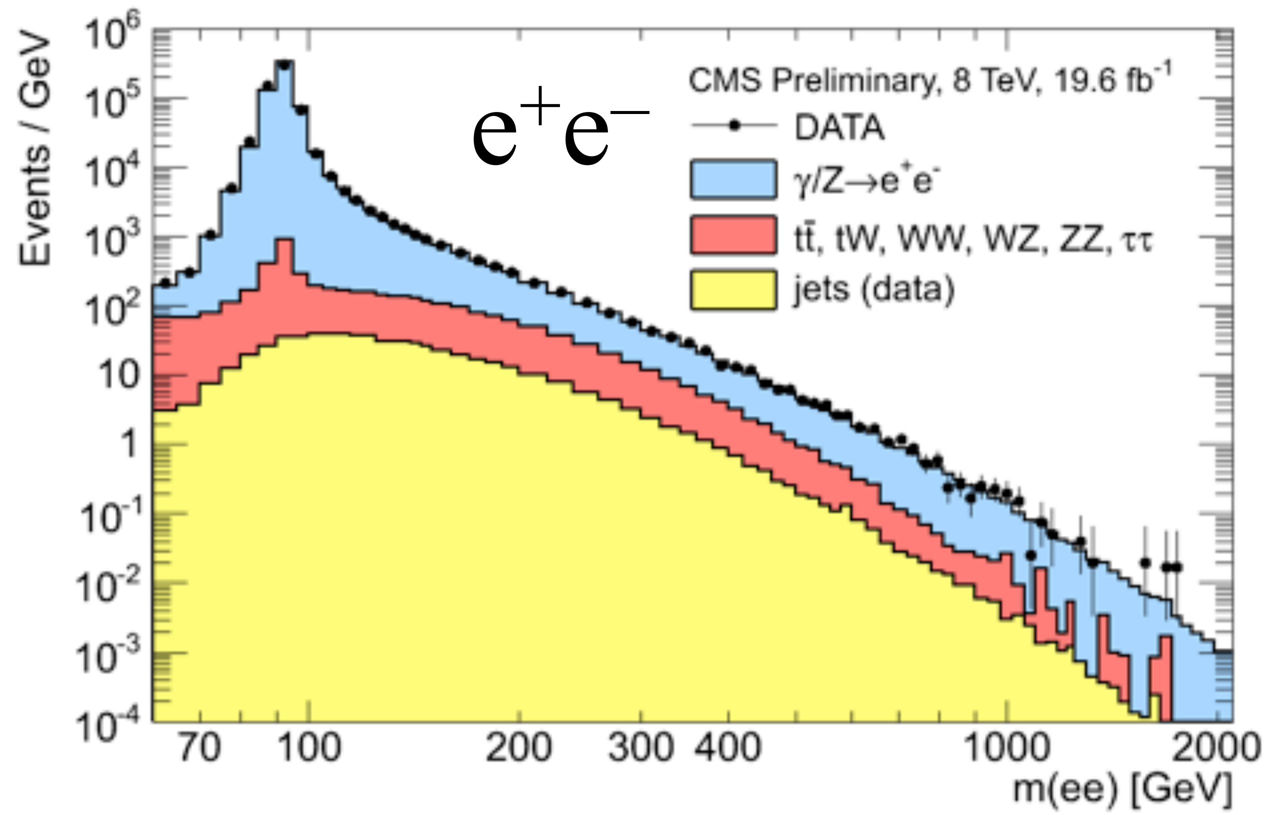
Dilepton searches

EXO-12-061

- Two high-p_T leptons
  - Selection is tuned to maximize the significance in $M_{\ell\ell}$
  - Requires different selection criteria + validation methods
    - Well-modeled in MC simulation
    - Use $e\mu$ data to verify

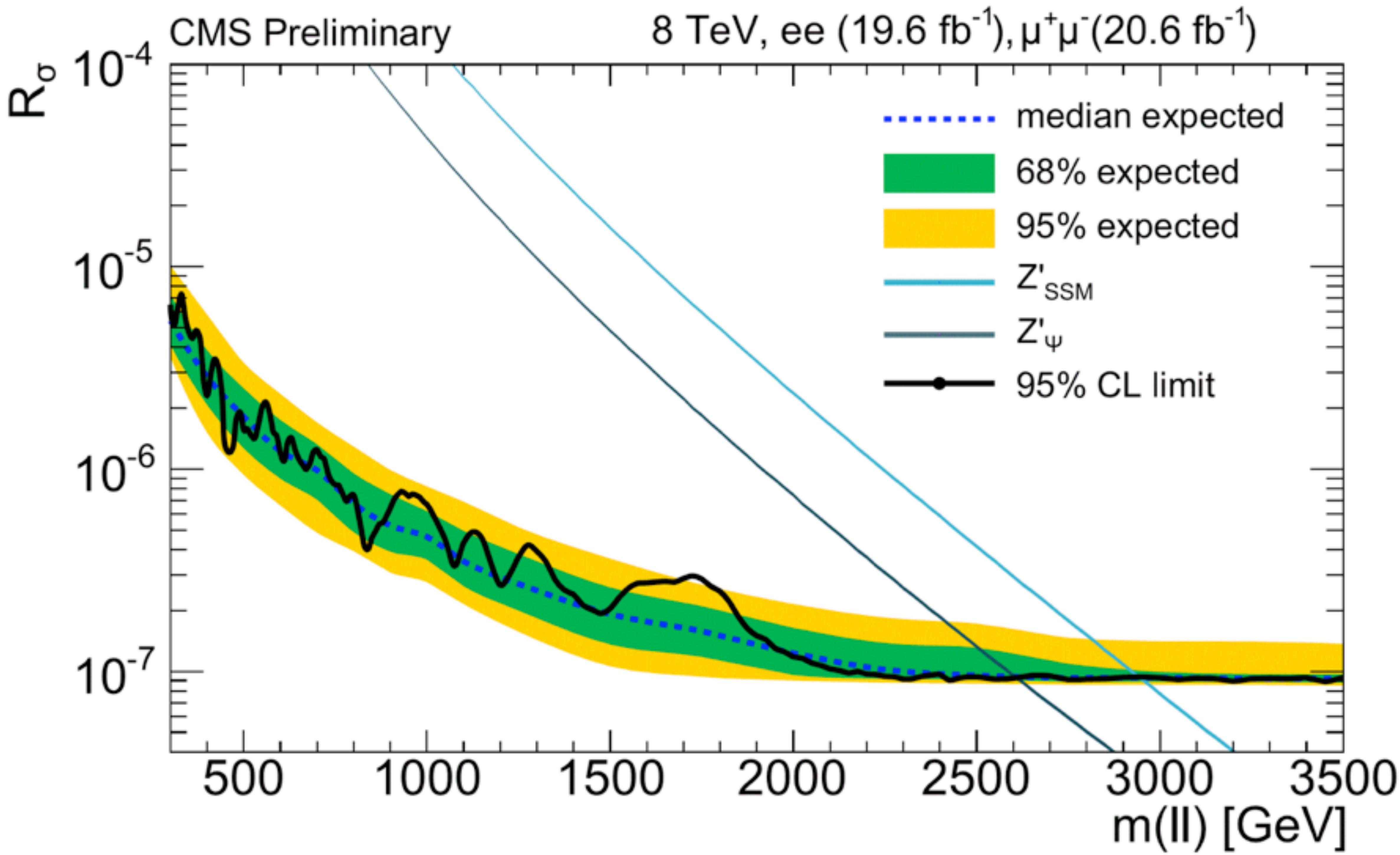






Dilepton searches

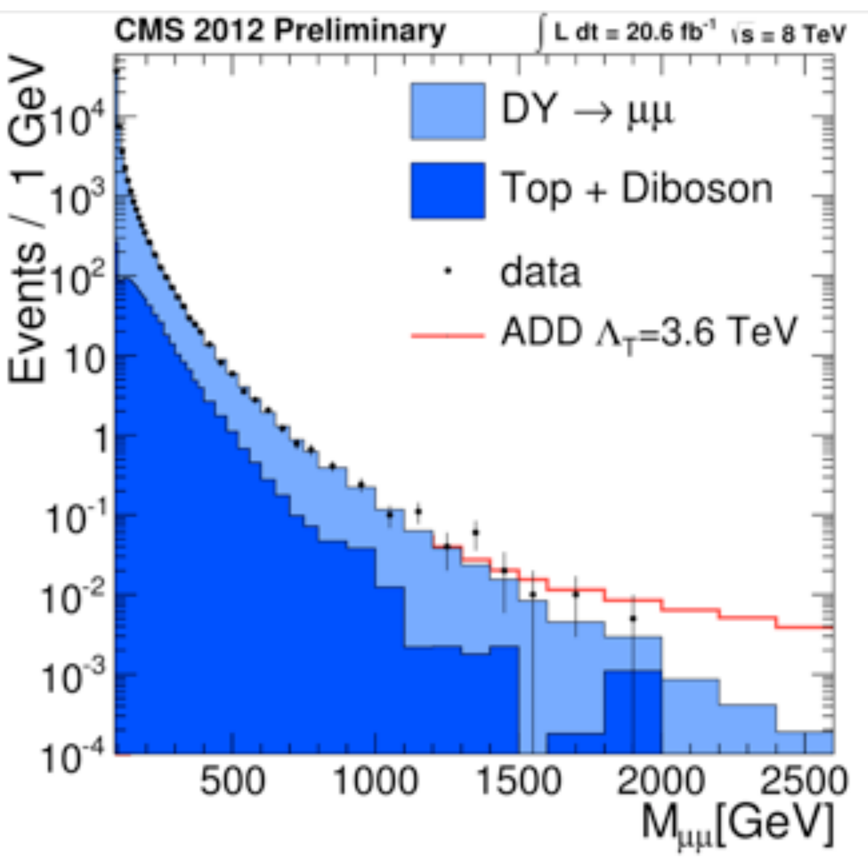
- No evidence for new physics

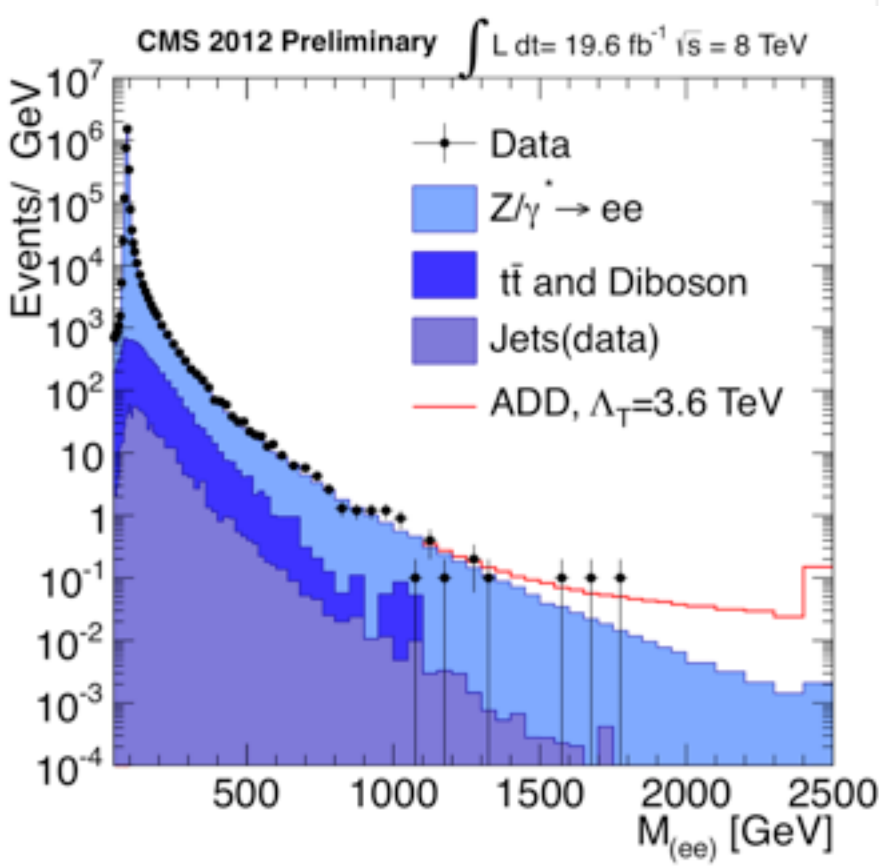


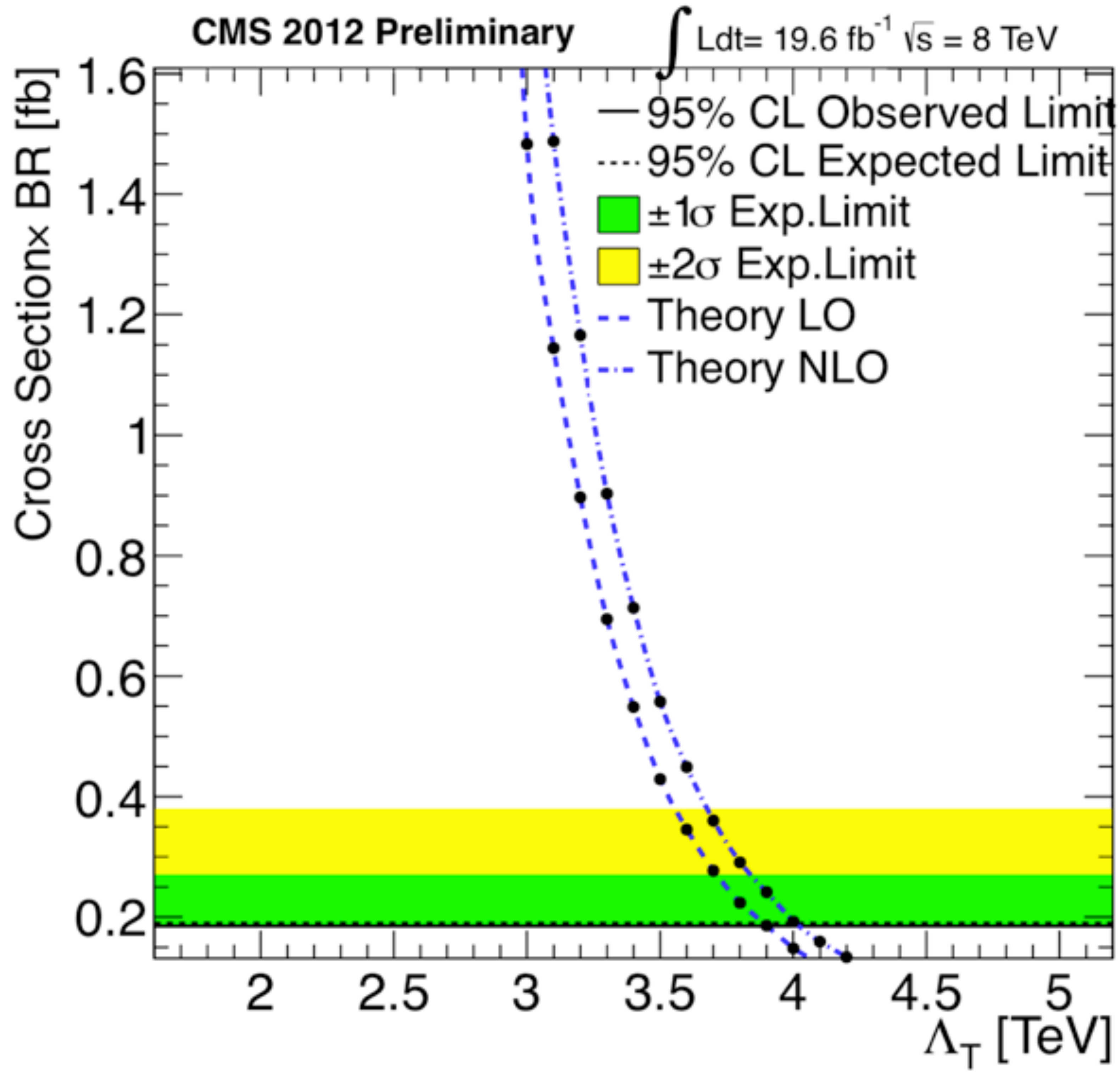
EXO-12-027

EXO-12-031

Search for LED







$M_S > 4.77$ TeV (ee)

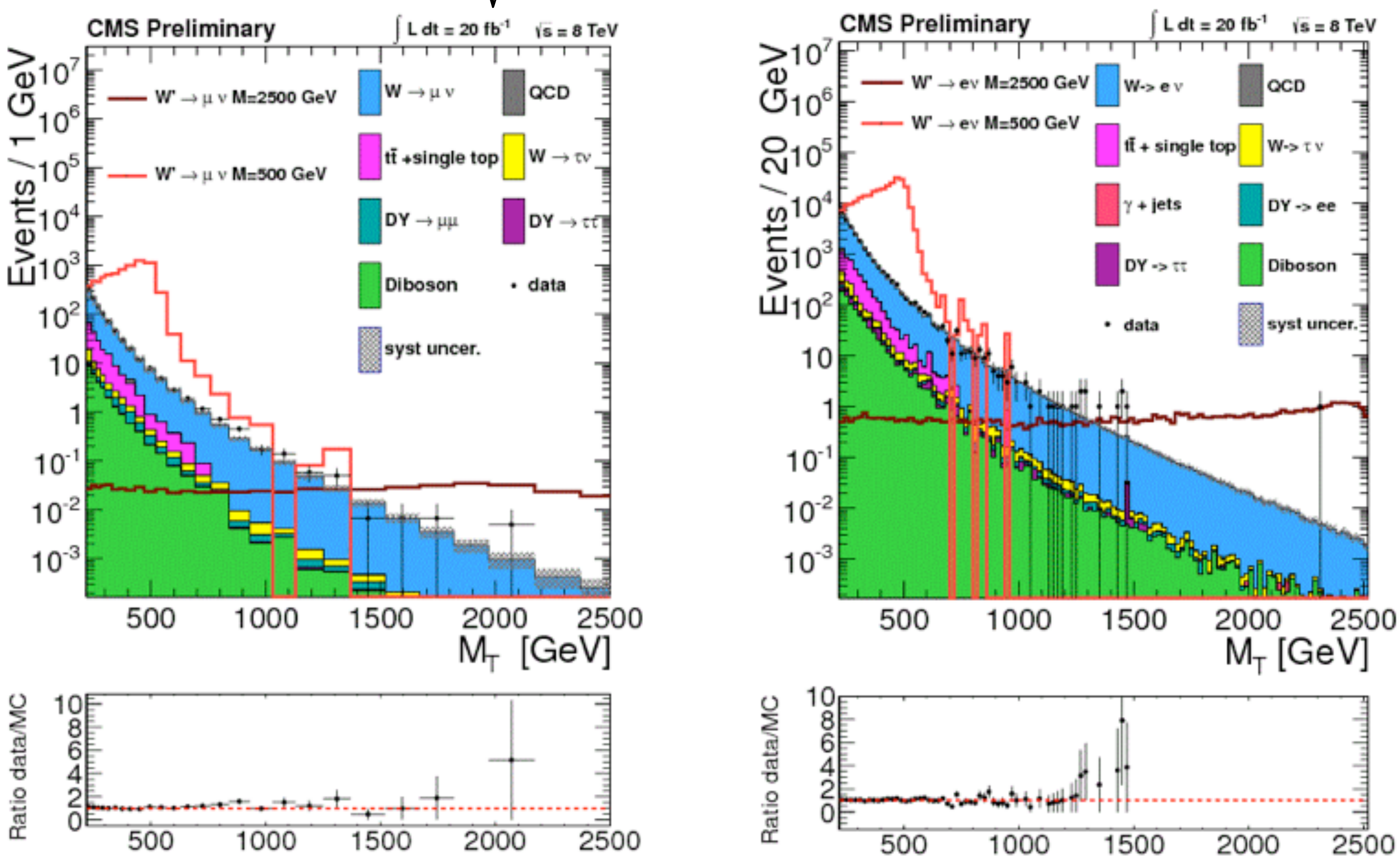
$M_S > 4.49$ TeV (μμ)

Search for W′

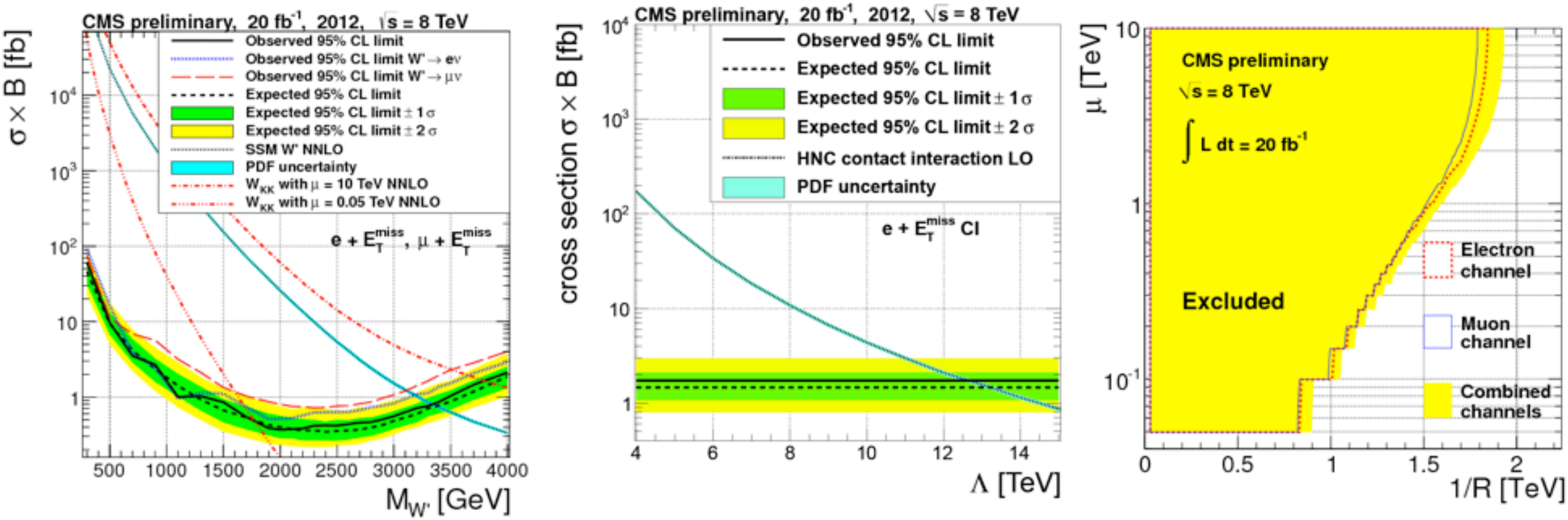
EXO-12-060

- One high-p_T isolated lepton
  - Backgrounds are estimated from simulation
  - Fit full MT at high masses to empirical function $\frac{a}{(M_T^3 + bM_T + c)^d}$

$$M_T = \sqrt{2p_T^\ell \cdot \mathrm{MET} \cdot (1 - \cos\Delta\phi_{\ell,\nu})}$$



Interpretation of W′ search



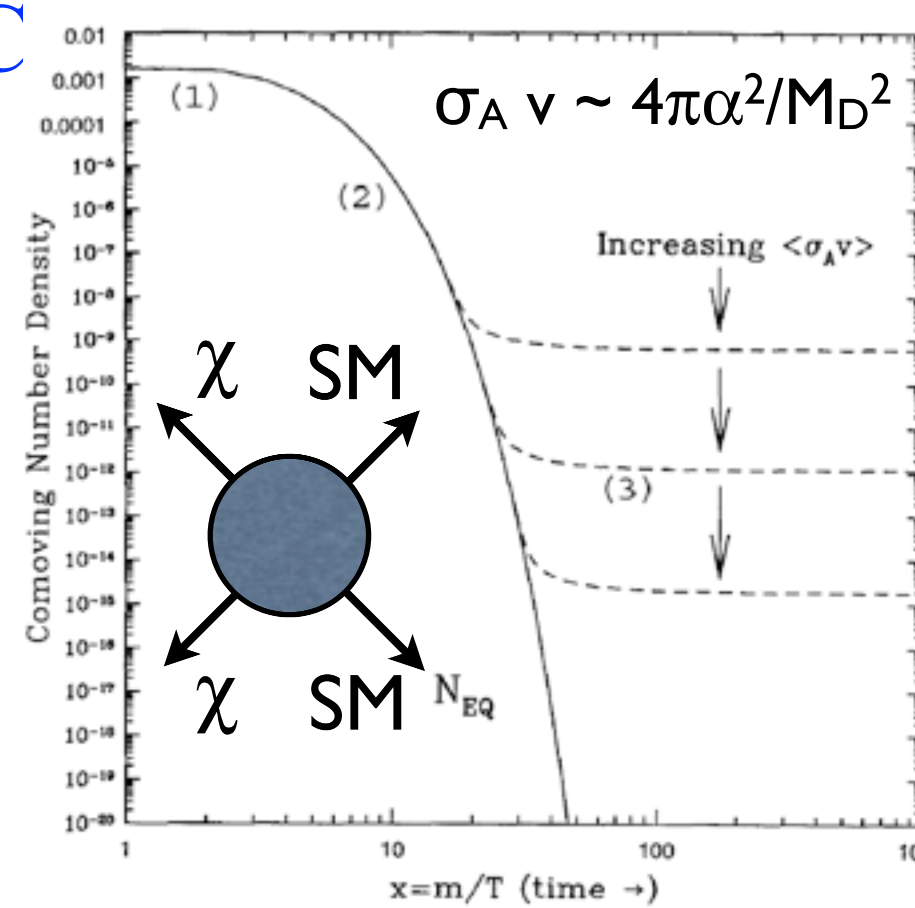
- Many interpretations
  - Excluded 3.35 TeV of W′ at 95% CL
  - Limits on contact interactions
    - Λ > 13.0 TeV (e+MET) and Λ > 10.9 TeV (μ+MET) at 95% CL
  - Limits on W_{KK} (split UED)

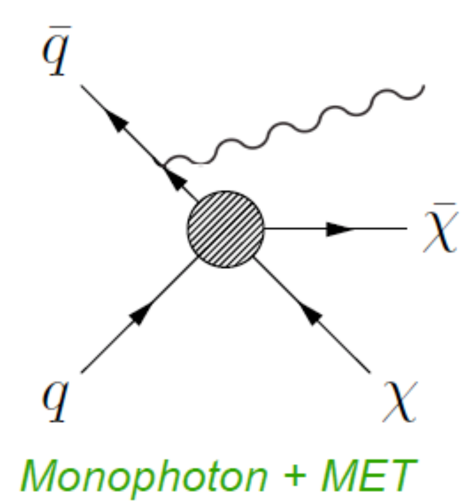
Searching for Dark Matter

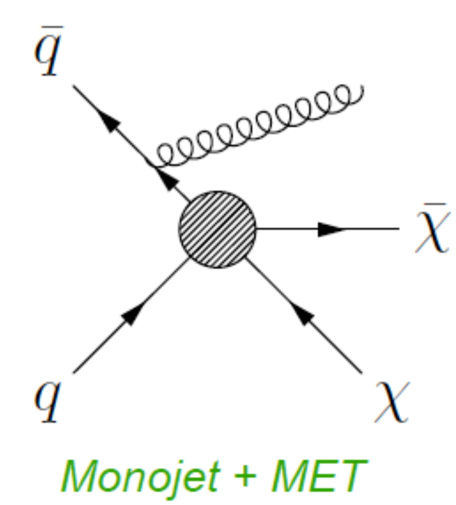
EXO-12-048

J. Feng 0801.1334v2

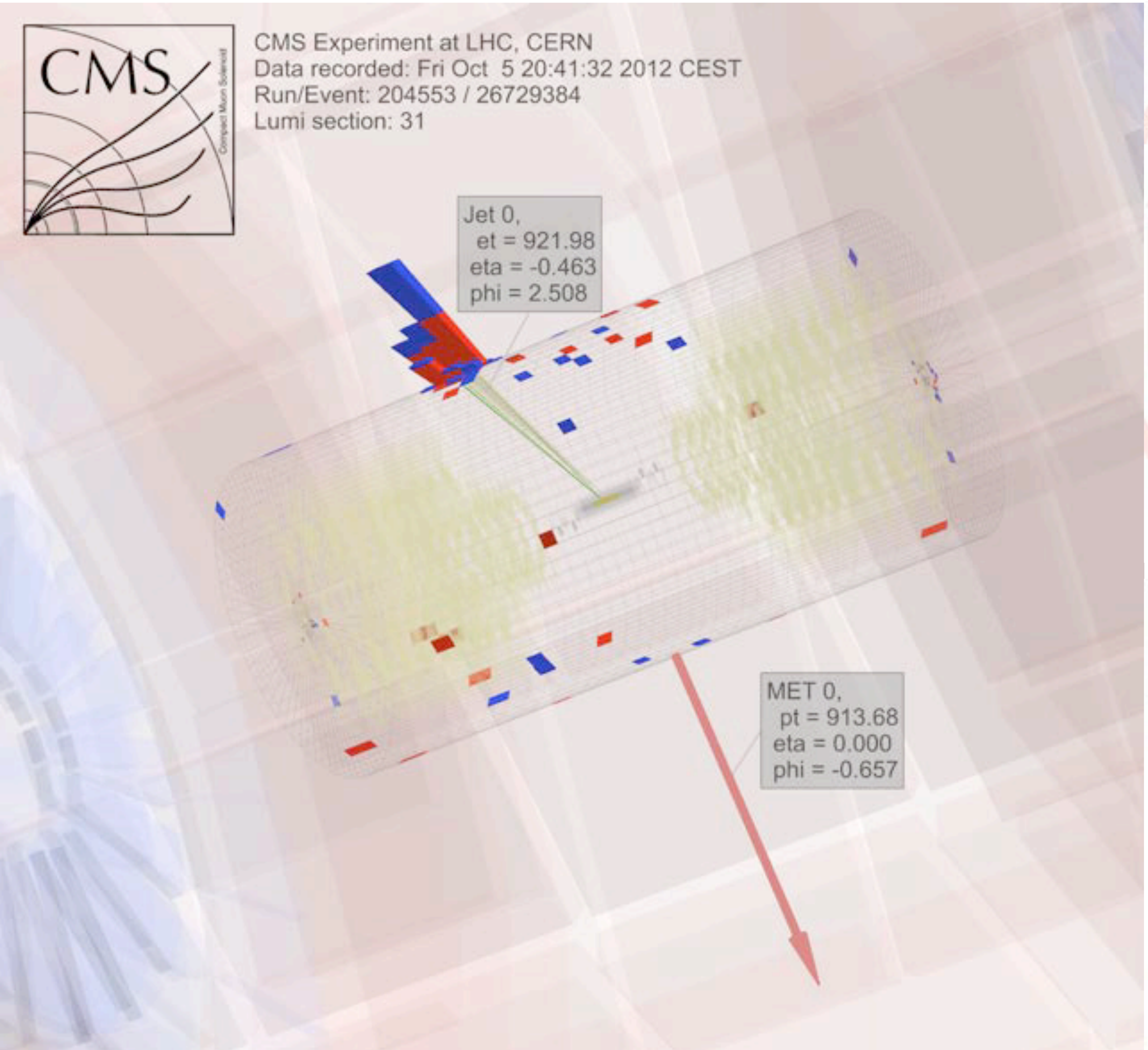
- Dark matter can be searched for at LHC
  - Probably produced in pairs
  - WIMP "miracle"
    - $M_D \sim 10$ - 1000 GeV to get Ω_{DM} right
- If you produce it at LHC in pairs you must find the trigger
  - Initial state radiation: γ+MET and jet+MET
- Same final state can be used to search for a number of interesting phenomena
  - ADD Large extra dimensions
  - Unparticle models
  - Light stop
  - Anomalous TGCs (γ+MET)

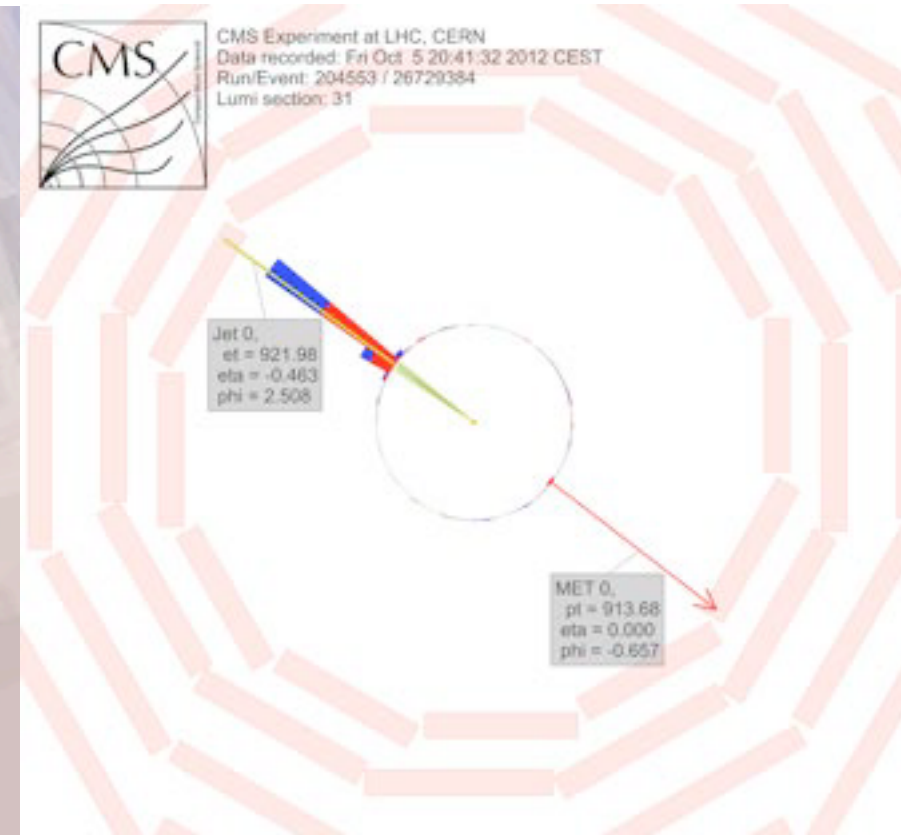


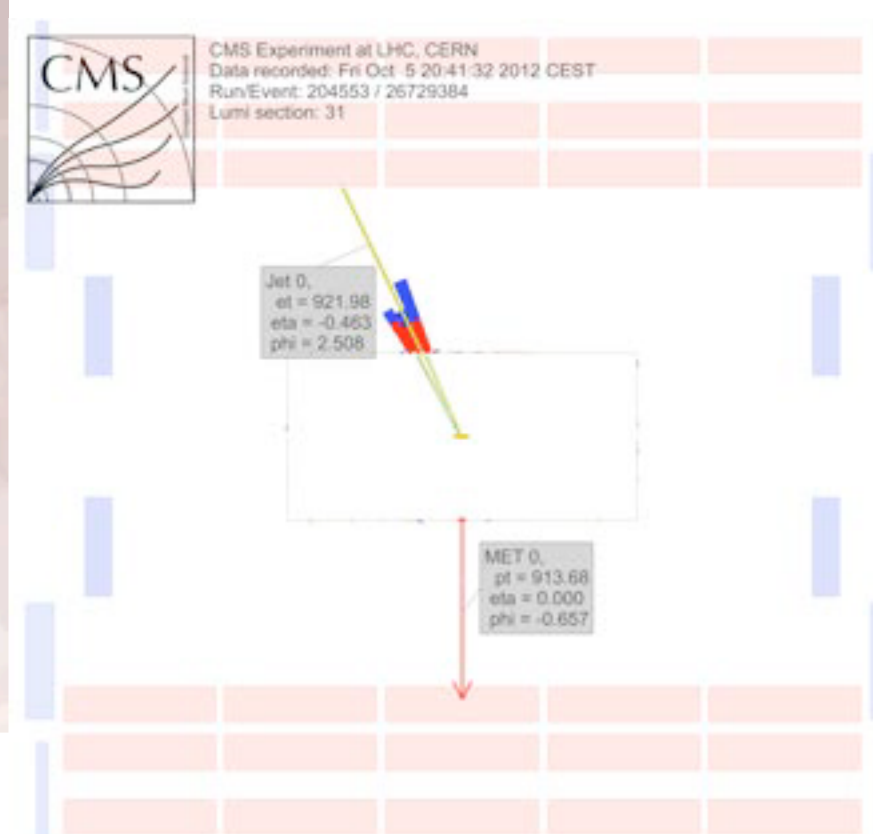




Example of signal event





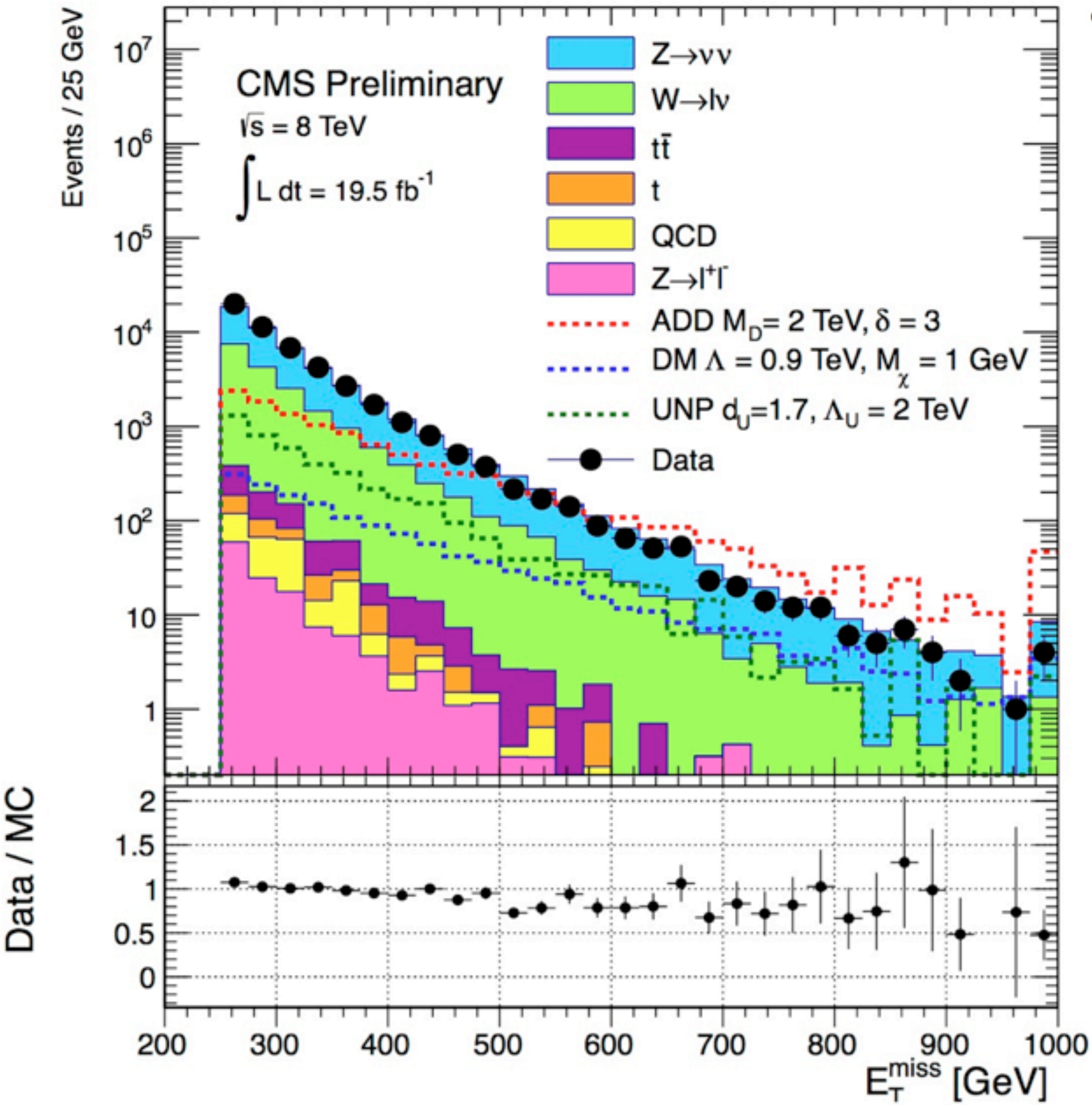


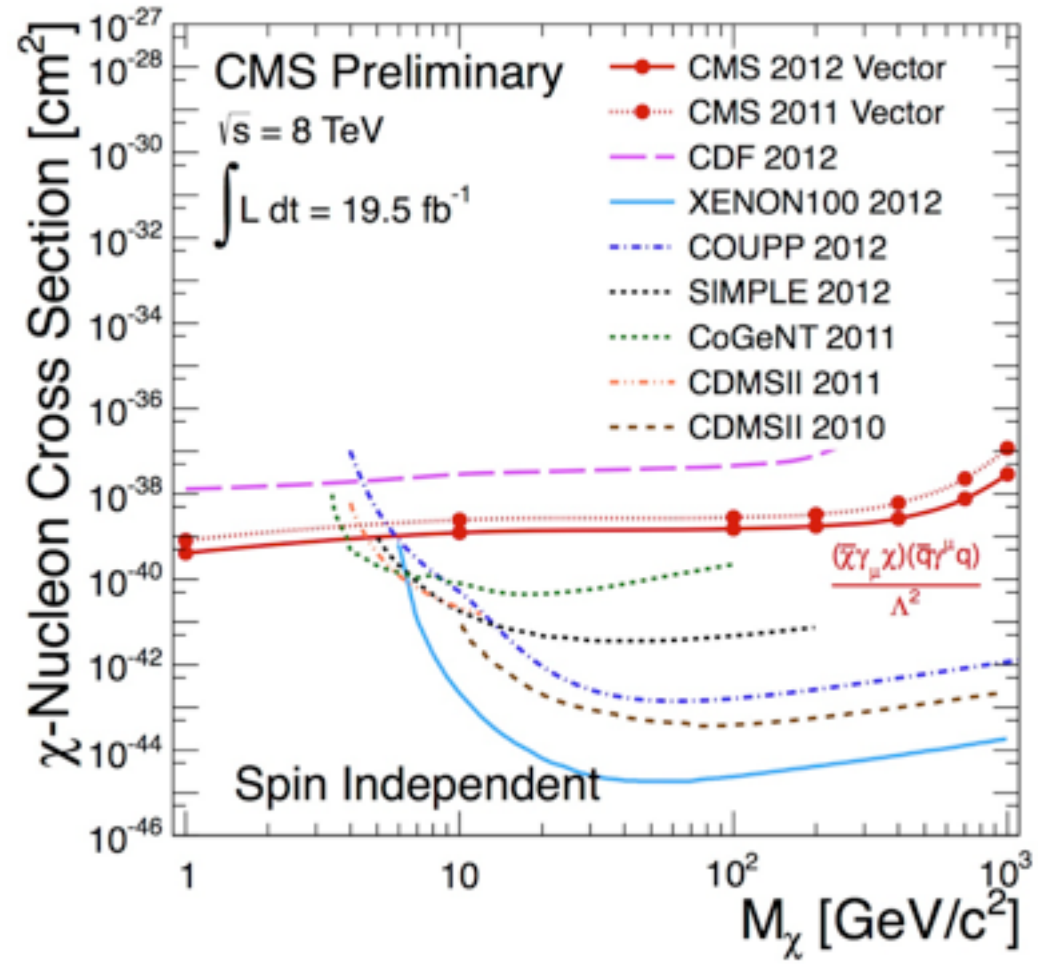
Event selection

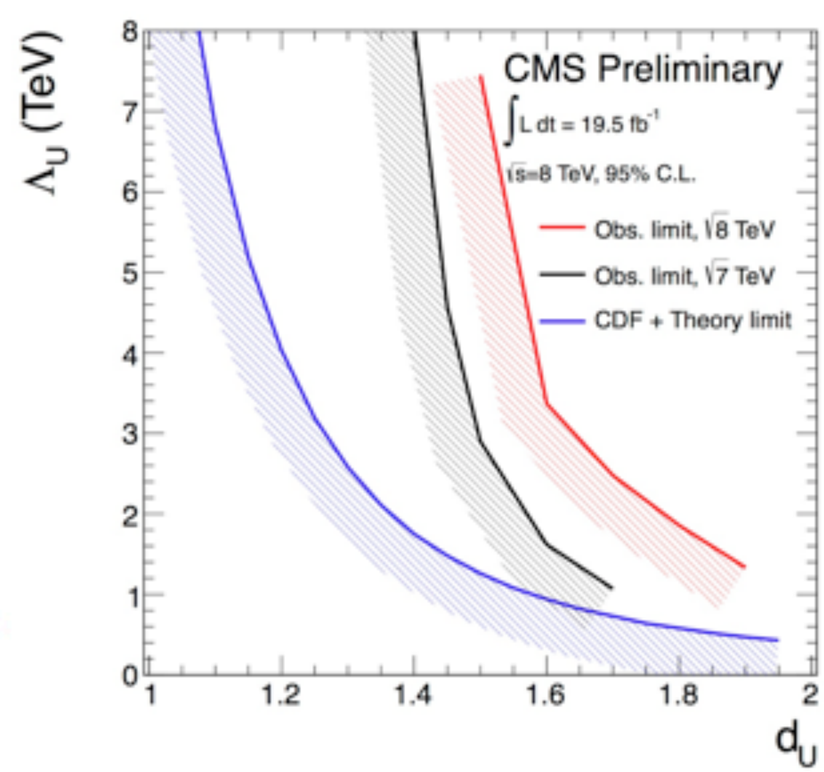
- Energetic jet + MET requirement
  - Require up to one extra jet, and no extra leptons
    - Use $\Delta\varphi_{j1,j2}$ to reduce QCD contribution
- Major backgrounds are estimated in data
  - Z+jet → $\nu\nu$ + jet (estimated from $Z\rightarrow\mu\mu$ data)
  - W+jet → misidentified lepton + ν + jet ($W\rightarrow\mu\nu$ data)
  - Multijets, Zjets, ttbar etc (estimated in MC simulation)

MET (GeV)	$Z\rightarrow \nu\nu$	W+jets	ttbar	Z+jets	t	QCD	Total	Data
500	671 ± 81	269 ± 20	6	2	1	1	949 ± 85	894
550	370 ± 58	128 ± 13	3	1	0	0	501 ± 60	508

Monojet results







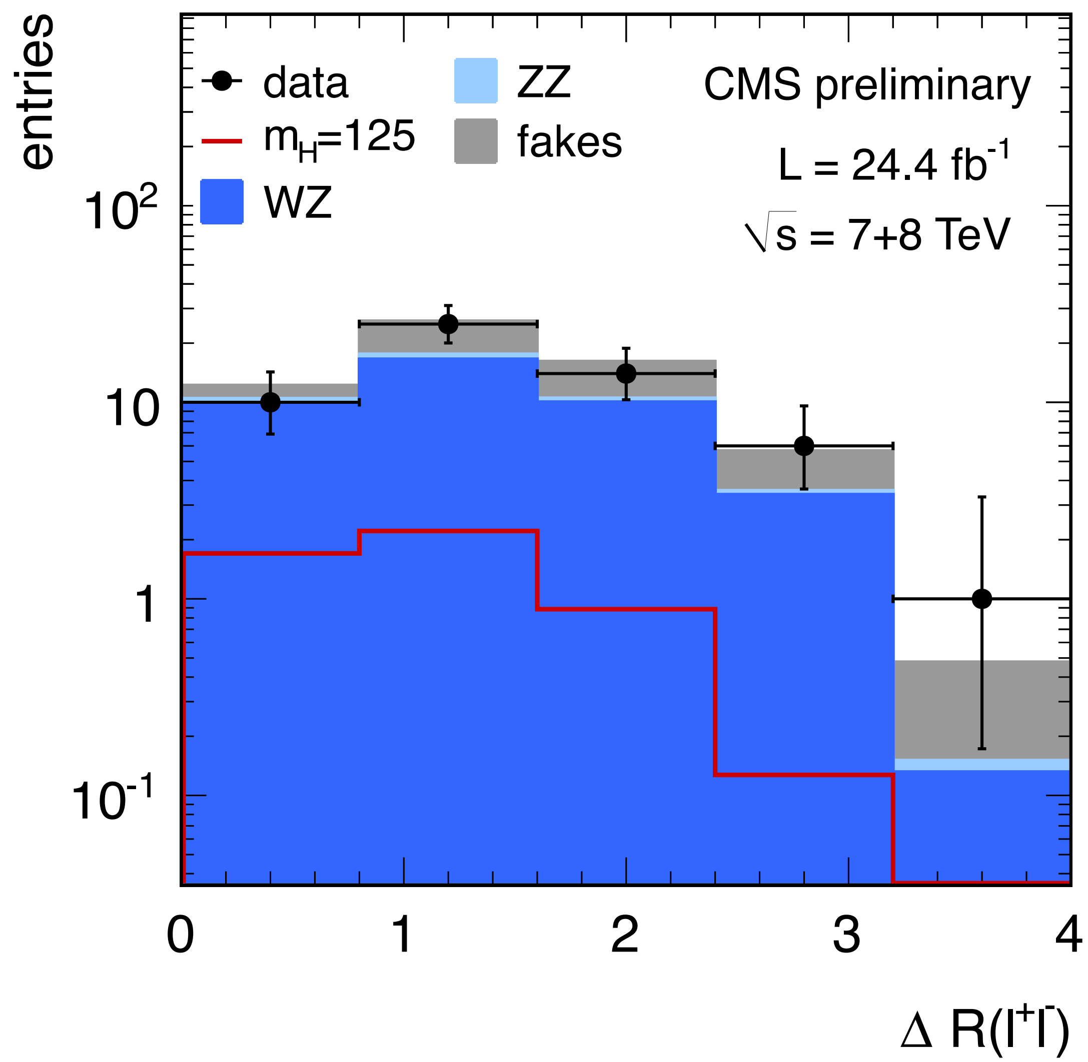
Current physics landscape

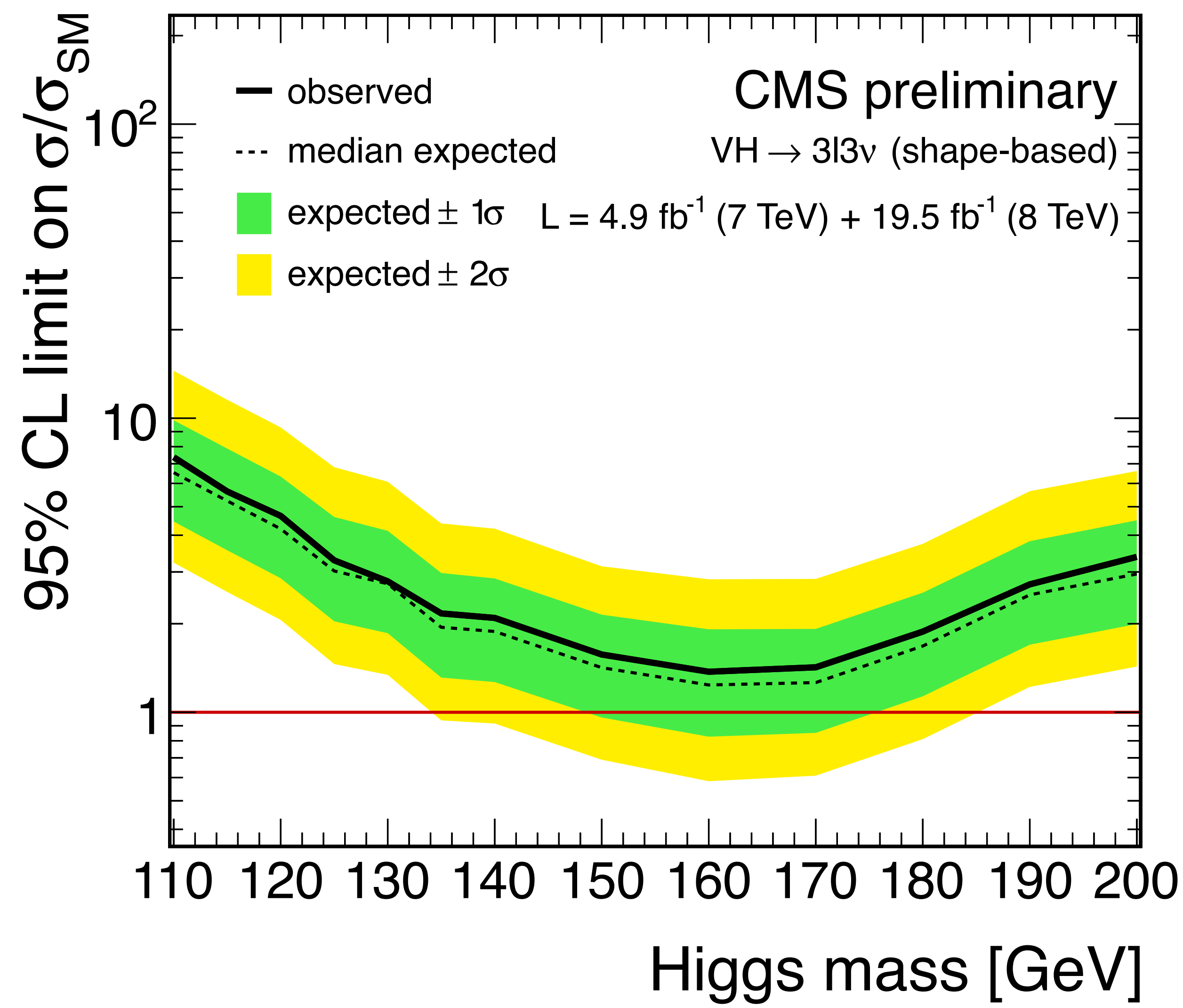
Summary

- We seem to discover the first fundamental scalar field
  - Spin-parity results are consistent with the SM Higgs and disfavor other considered scenarios; signal strengths are consistent with the SM prediction as well.
  - Mass is 125.8 ± 0.6 GeV
  - *More results to follow later this summer*
- A lot of experience with data analyses at Run 1
  - Rather complex searches, pushing capabilities of the hardware to its fullest (but still a lot of things can be improved for Run 2!)
- No evidence for physics beyond the SM so far
  - Is new physics that control the Higgs mass is right around the corner? Or do we live in a very unnatural Universe?

Backup

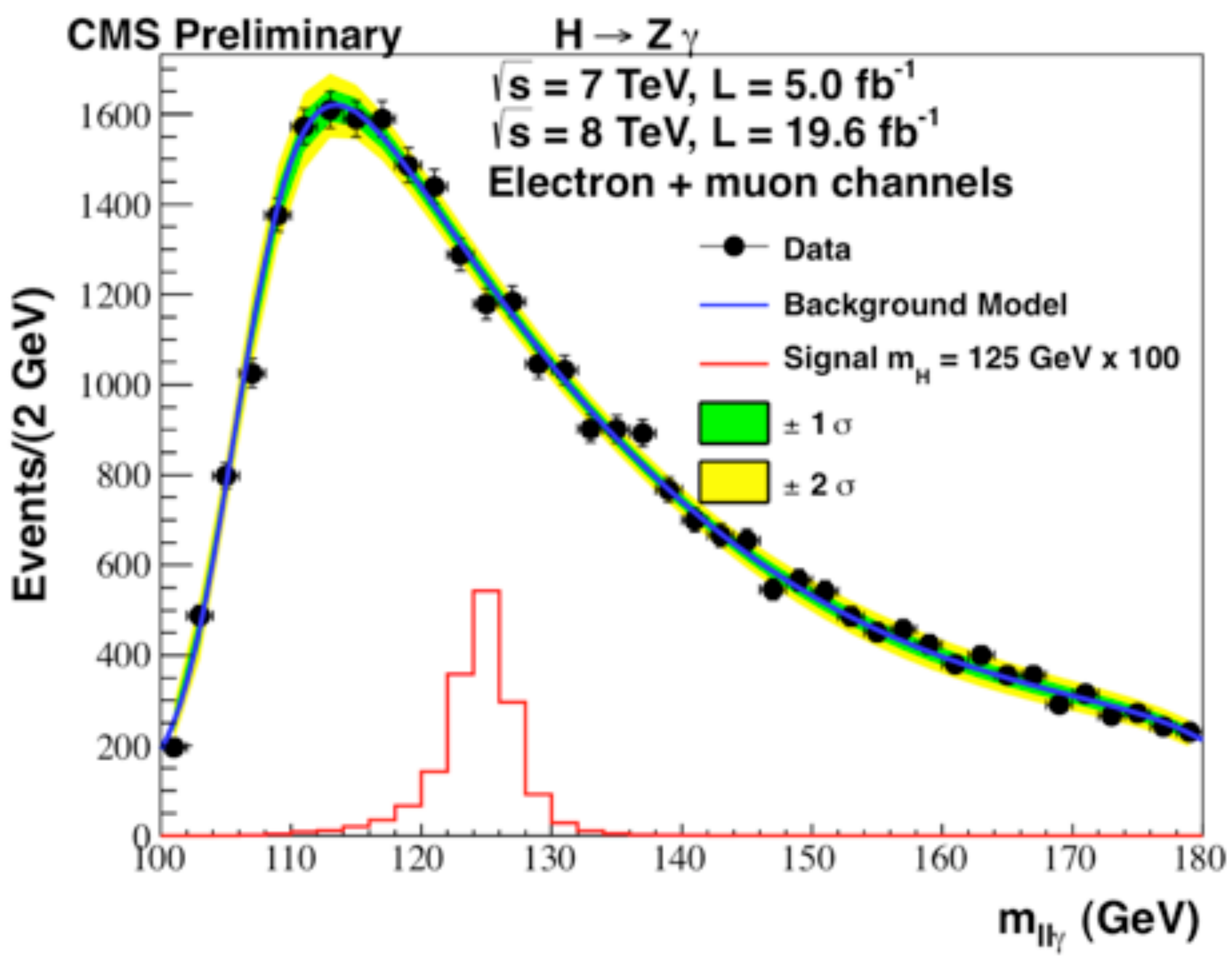
WH→WWW→3ℓ3ν

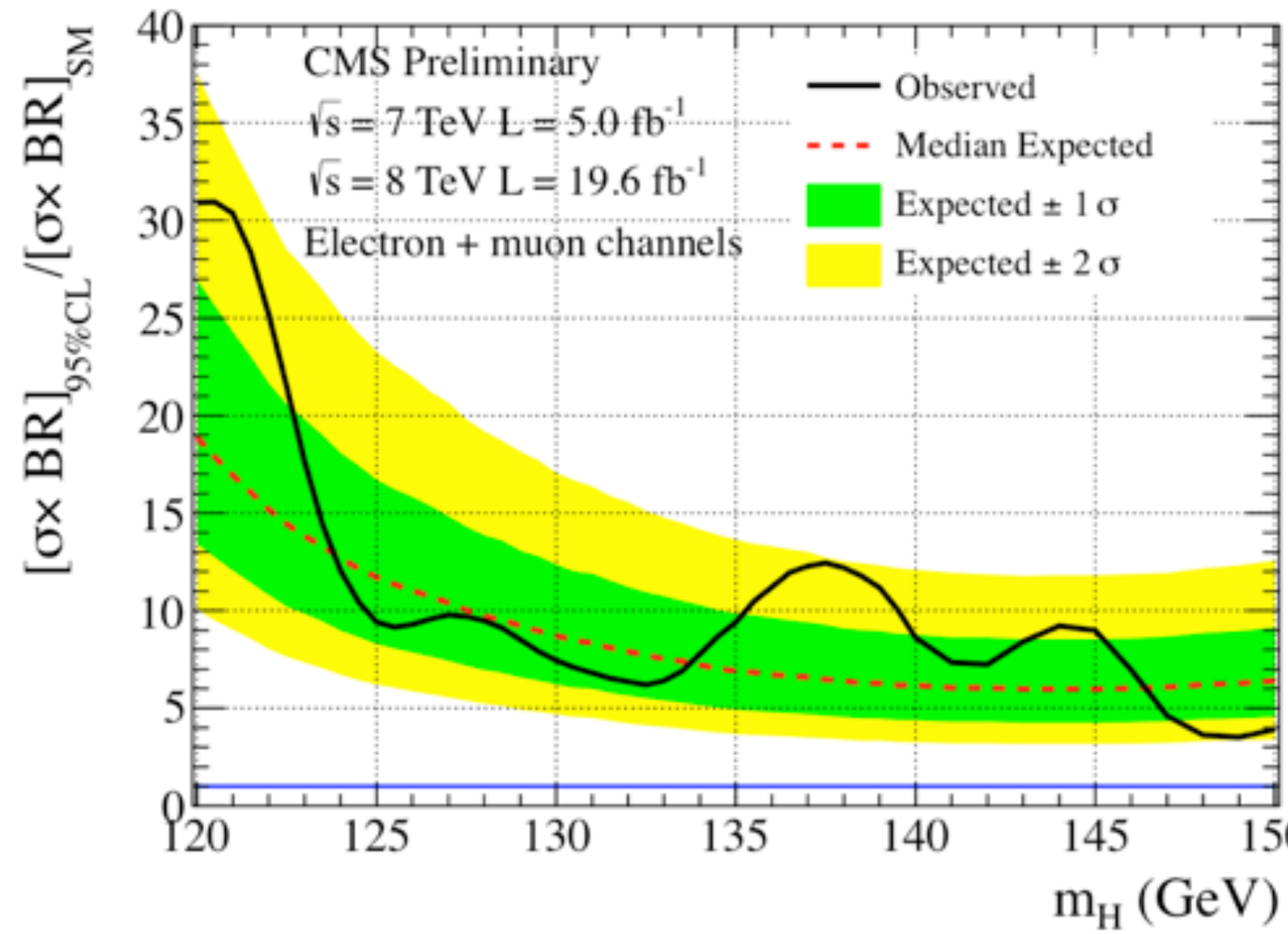




- Final state: three high-pT leptons (e or μ) and MET
  - Veto Z candidates and b-jets to reduce WZ and top events
- Two approaches: cut- and shape-based using $\Delta R_{\ell^+\ell^-}$

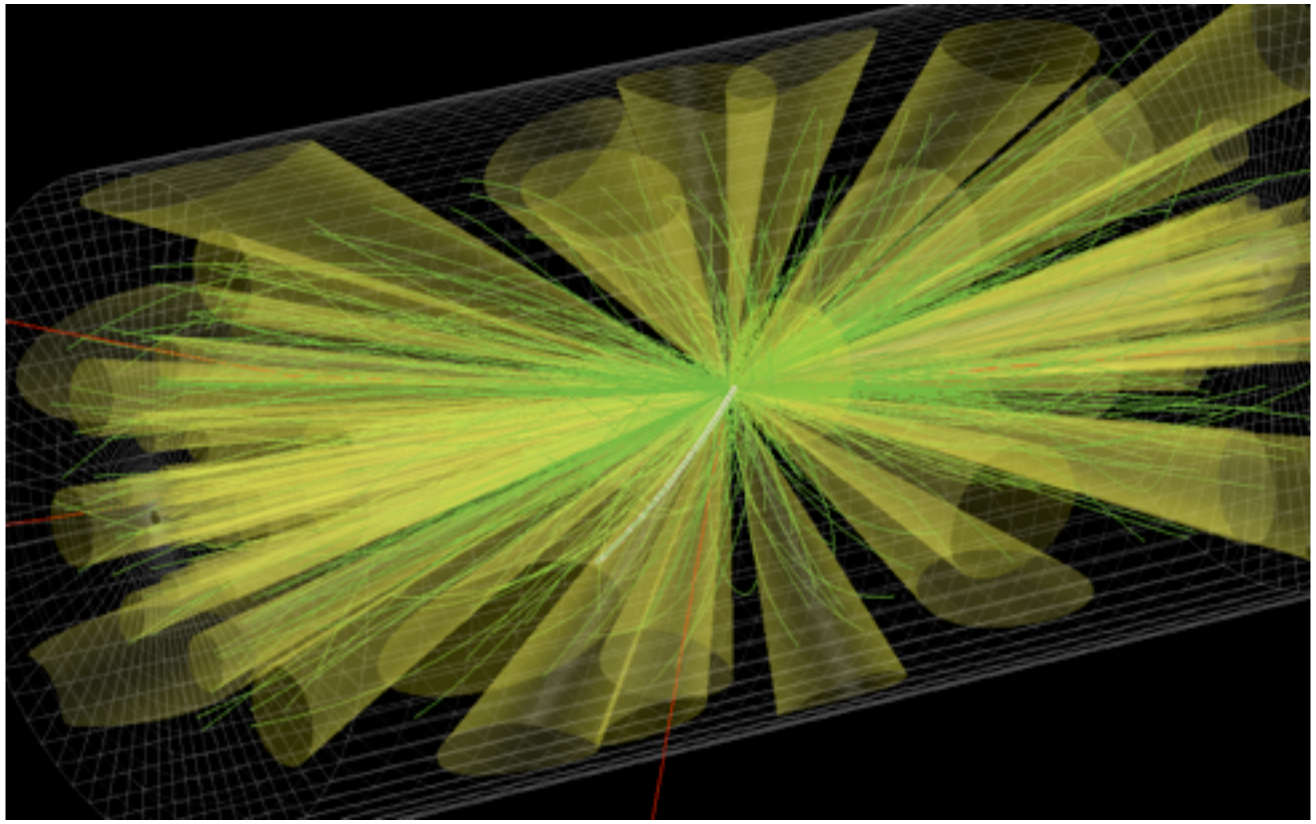
H→Zγ

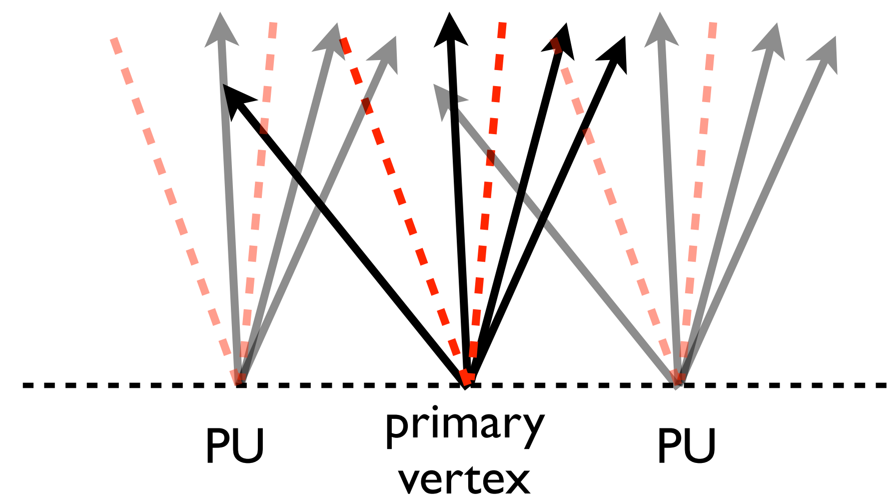




- Use muon and electron Z decays
- Four event categories based on event topology and whether photon converted or not
  - Improves S/B and mass resolution

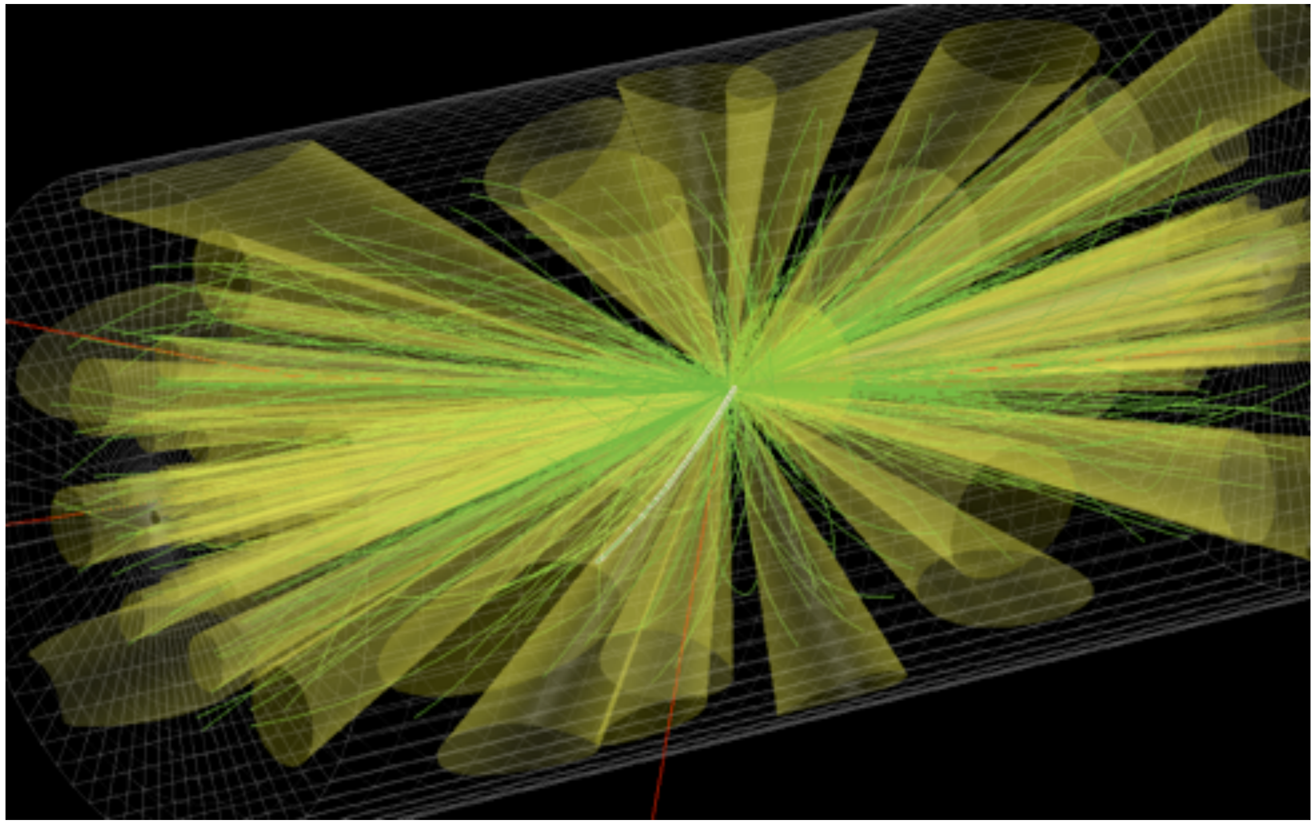
Pileup and isolation

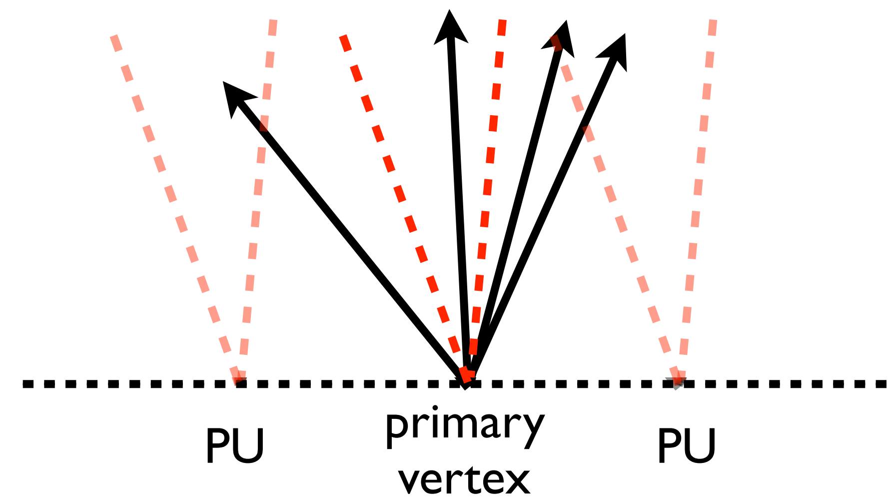




- Charged particles are considered from the primary vertex only (electrons, muons, charged hadrons)
  - Removes the pileup contribution from charged particles
- Neutral contribution is subtracted on average using FASTJET simulator arXiv:1111.6097

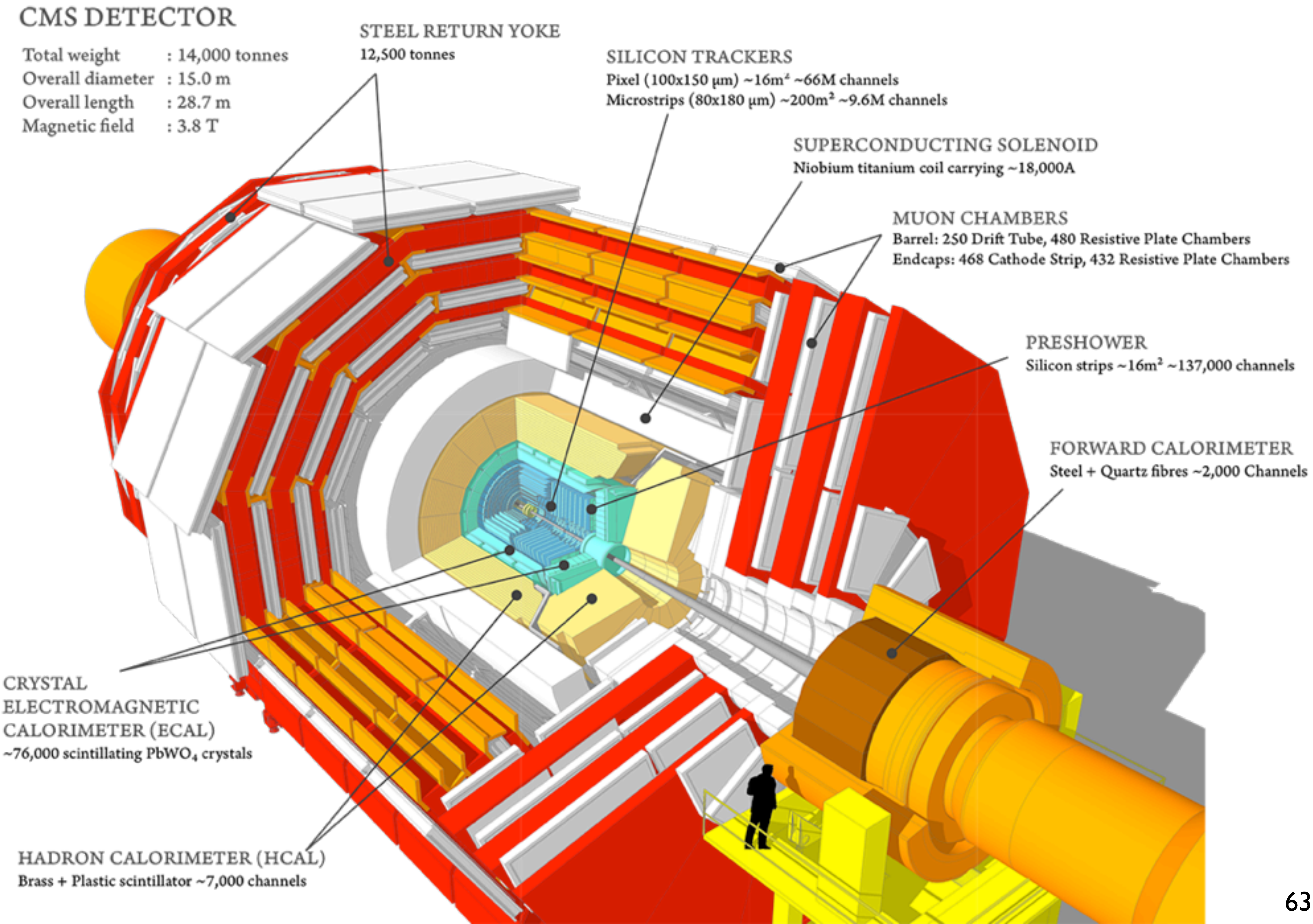
Pileup and isolation



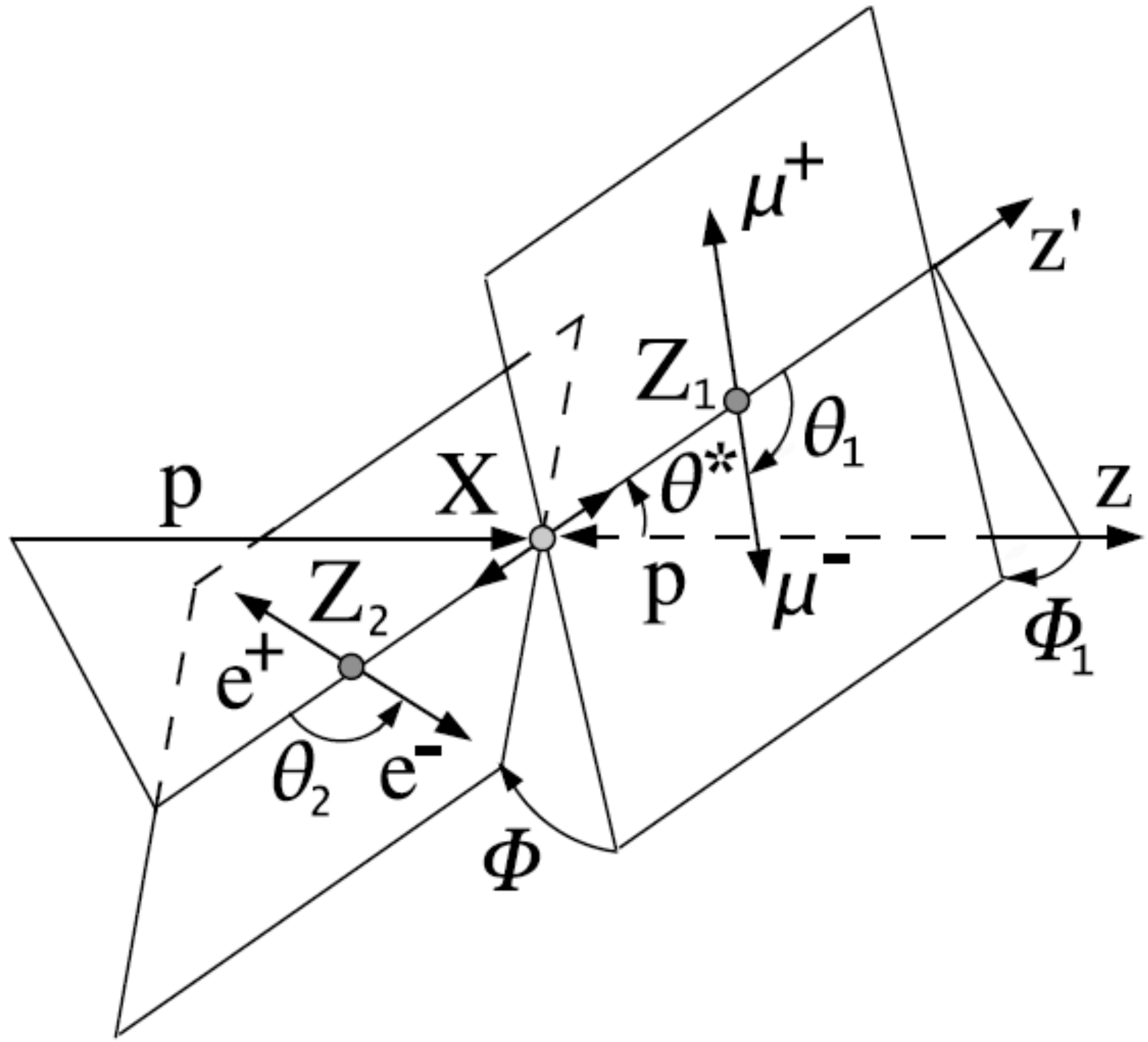


- Charged particles are considered from the primary vertex only (electrons, muons, charged hadrons)
  - Removes the pileup contribution from charged particles
- Neutral contribution is subtracted on average using FASTJET simulator <u>arXiv:1111.6097</u>

CMS Detector

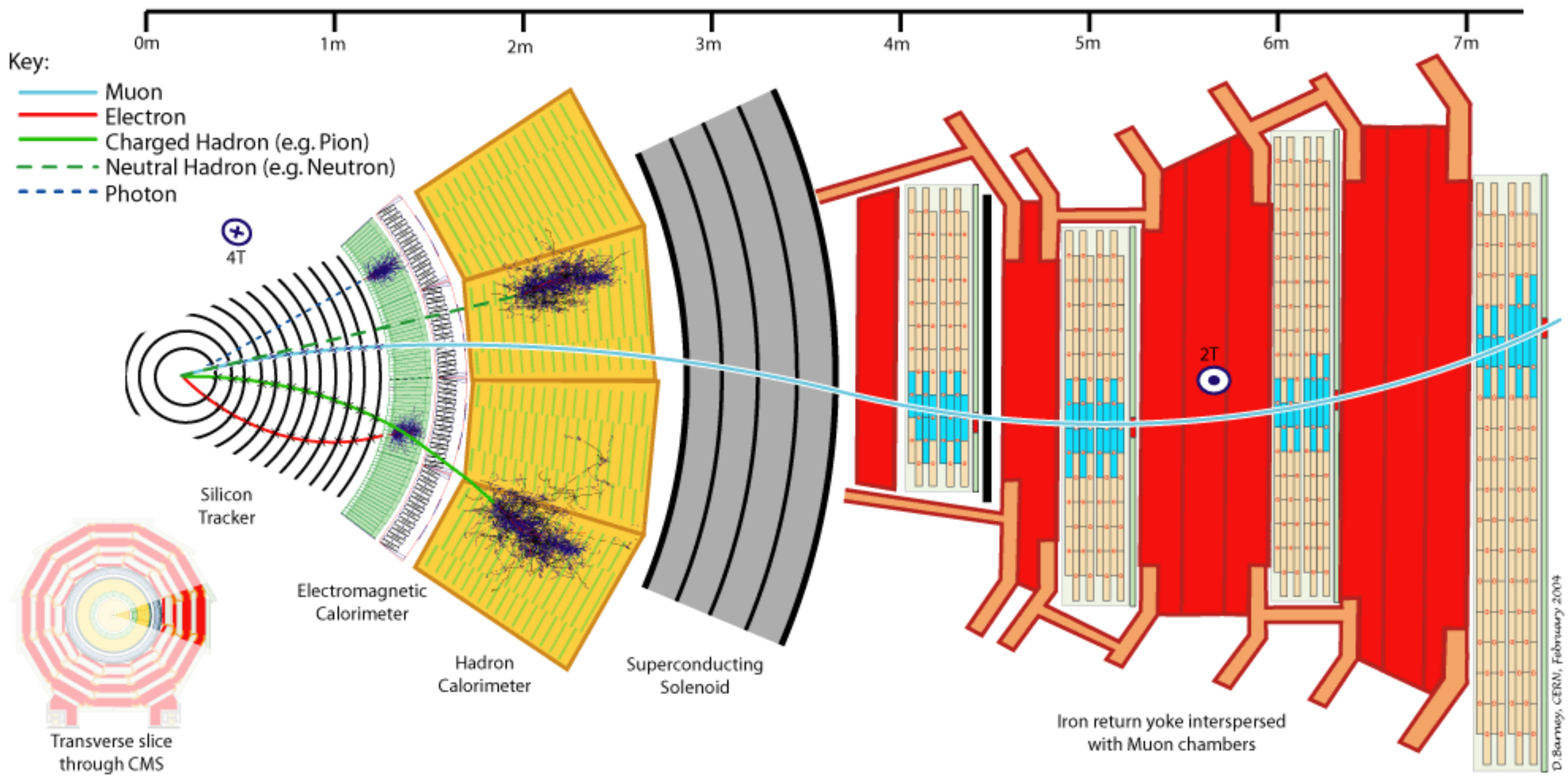


X→ZZ→4ℓ angles



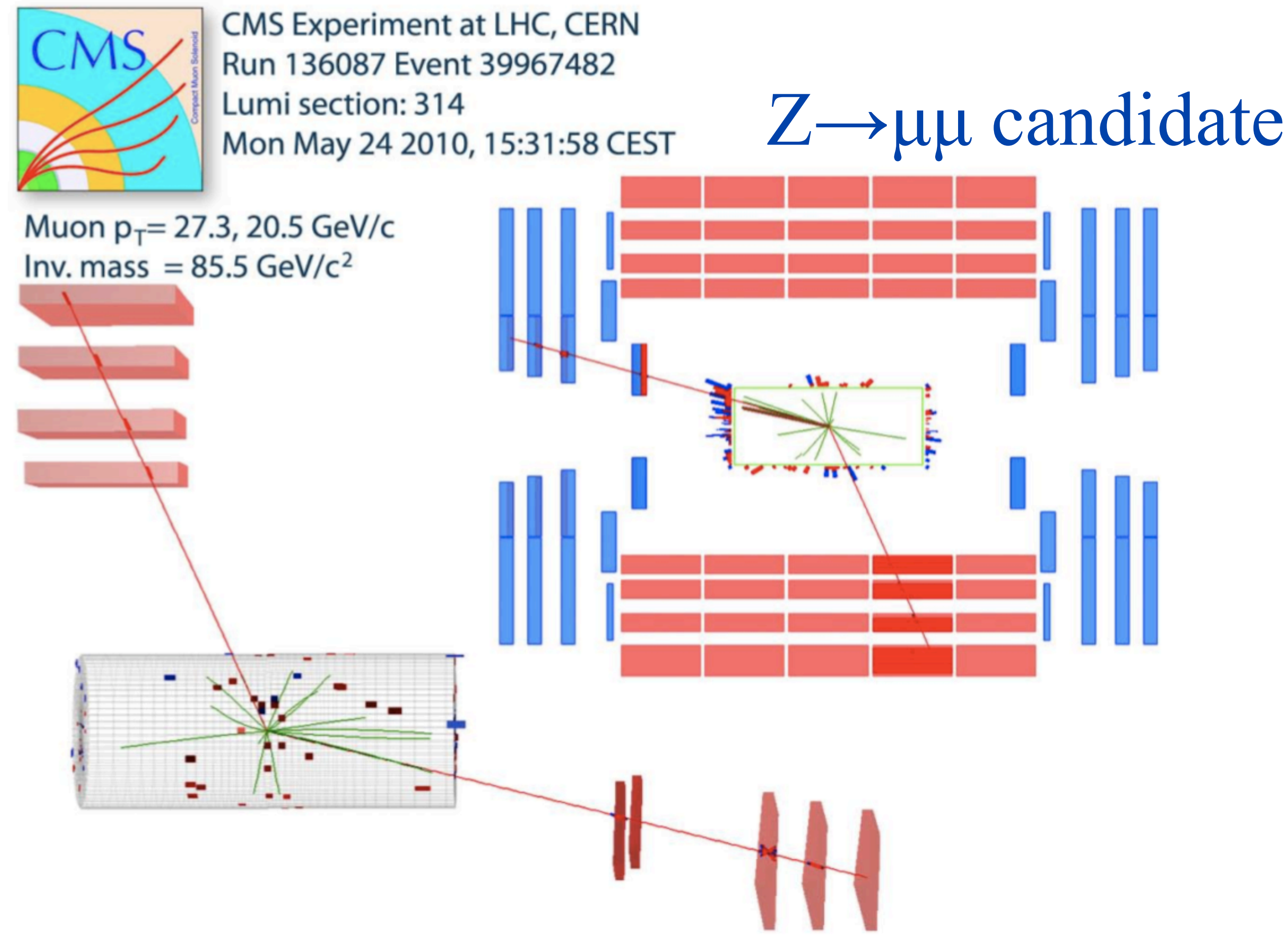
- Illustration of production angles θ* and φ_1 of a particle X production in X rest frame and three decay angles θ_1, θ_2, and φ in the P_i rest frames

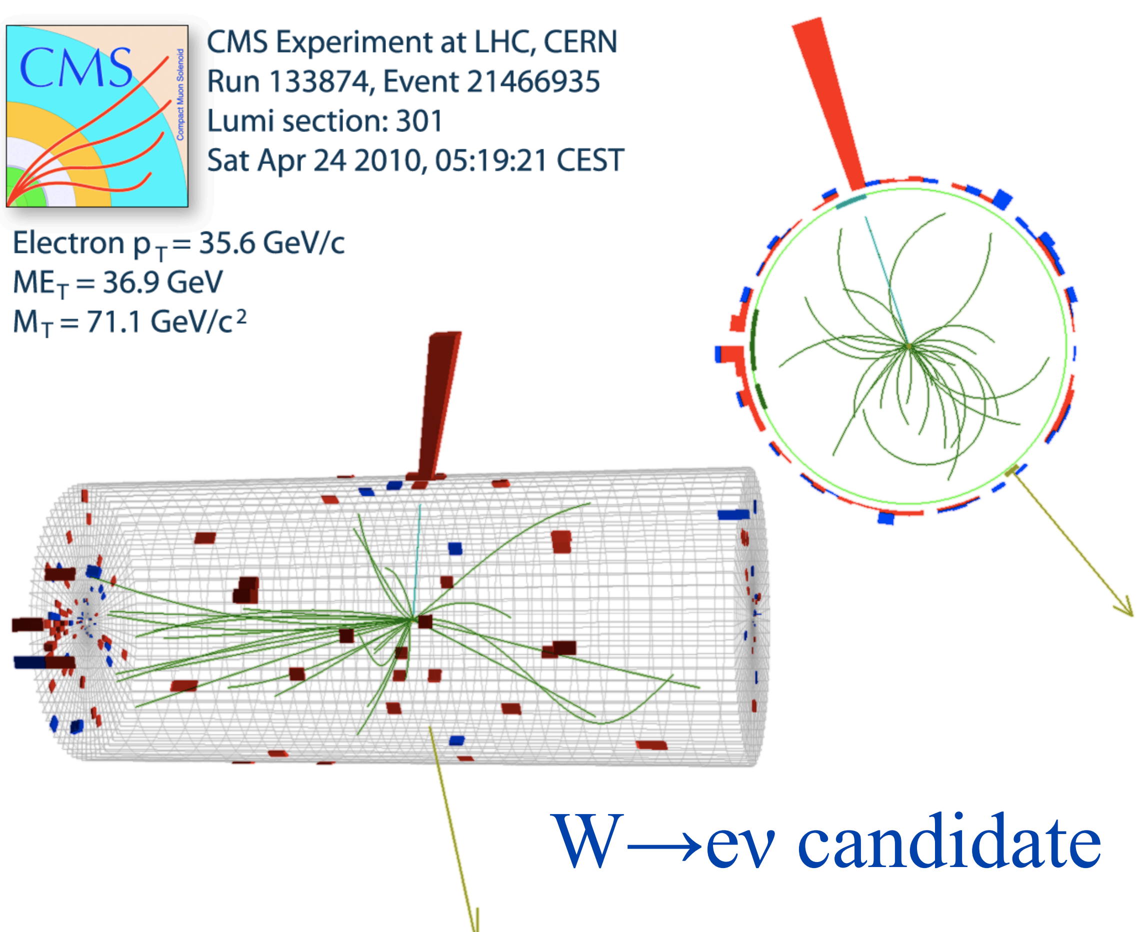
CMS detector



Lepton identification

- Muon resolution dominated by inner tracking for $p_T < 200$ GeV
- Typical p_T resolution ~1-2%
- Muon chambers offer redundant trigger and coverage
- Muons can be reconstructed both in inner tracker and muon chambers

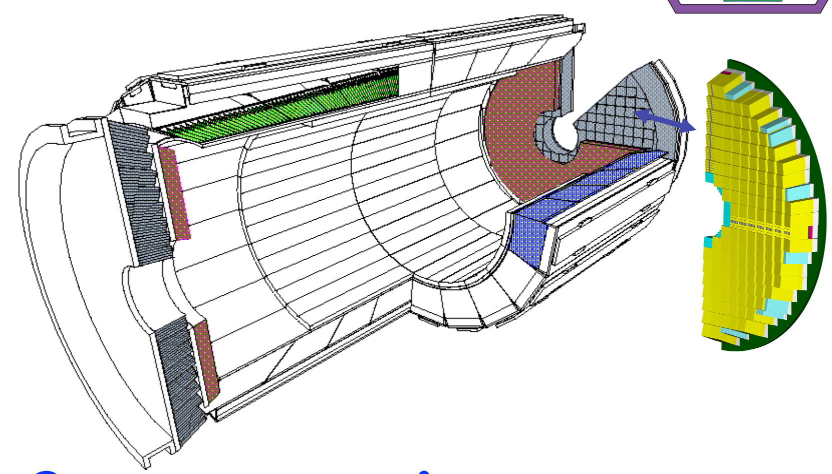




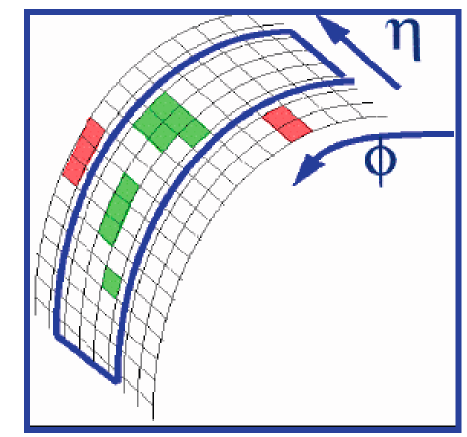
- Excellent resolution provided by the $PbWO_4$ crystal calorimeter
- Typical E_T resolution is ~1-2%
- Electron identification is based on shower shape variables, ECAL-Tracker matching and HCAL/ECAL energy ratio

Photon identification

- Highly segmented CMS ECAL
  - 80,000 $PbWO_4$ crystals
  - Excellent design of ~0.5% constant term



- Photons are identified as clusters of energy in ECAL that divided in two categories
  - For unconverted photons: matrix of 5x5 crystal
  - For converted photons: super cluster: φ x η area



Transparency